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Evaluation and improvement of Mini-Ranger network in Monterey Bay for oceanographic purposes

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THESIS

EVALUATION AND IMPROVEMENT OF
MINI-RANGER NETWORK IN MONTEREY
BAY FOR OCEANOGRAPHIC PURPOSES.

by

Nickolaos G. Krioneritis

December 1989

Thesis Advisor Kurt J. Schnebele

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In order to undertake this task, data were made available by MBARI which were collected on a cruise made by their vessel "Pt. Lobos". Additional data were gathered on a second cruise by the vessel "Pt.Sur" of the NPS.
The data analysis indicated network problems. An effort was made to identify these problems and to compute various correctors. In addition, an equation has been derived which enables use of Mini-Ranger data collected when signal strengths are low.
The estimation of the accuracies obtained from the network through the various tests applied, and the conclusions drawn, can be used as a guide to future users of the system.

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Evaluation and Improvement of Mini-Ranger Network in Monterey Bay for Oceanographic Purposes.

by

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Submitted in partial fulfillment of the
requirements for the degrees of

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ABSTRACT

The purpose of this thesis was to evaluate the accuracy of the existing Mini-Ranger network in Monterey Bay and to suggest means by which the network can be improved. This network consists of six stations located around the Bay and installed by the Monterey Bay Aquarium Institute (MBARI) and the Naval Postgraduate School (NPS).

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The estimation of the accuracies obtained from the network through the various tests applied, and the conclusions drawn, can be used as a guide to future users of the system.

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I. INTRODUCTION

In 1988, the Monterey Bay Aquarium Research Institute (MBARI) and the Naval Postgraduate School (NPS) began work to create a permanent network of Mini-Ranger stations around Monterey Bay. The net was to provide precise positioning for research vessels and other scientific operations. Initially MBARI was seeking coverage of as much of the bay as possible, especially the Monterey canyon feature, with absolute horizontal position acuracies on the order of a few meters. It was understood this would be difficult to achieve, given the equipment's specified range (40 nm). This study was undertaken to determine what levels of accuracy and spacial coverage were being achieved, as the net was configured in early 1989, and also to suggest possible improvements.

Positioning data from two cruises were examined, one from a "Point Lobos" cruise on 31 MAR 89, and a second from "Point Sur" cruise on 22 SEP 89 (the "Point Lobos" and "Point Sur" are vessels used by MBARI and NPS, respectively). Significant errors were found in a high percentage of the position fixes from the "point Lobos" data set. It was apparent that at least some of the problem arose from the use of weak signals (low signal strength readings) and incompletely calibrated equipment. Consequently, additional measurements were made onshore over known length baselines in order to quantify the systematic and random error components of the range measurement under various signal strength conditions.[1]These findings stimulate the direction of the rest of the study:

- What were the main sources of errors?
- Is there any postprocessing that can correct the data and derive better positions?
- What is a realistic estimate of the accuracy achieved?
- Are there any chances for improvement?

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1 It should be noted that the "Point Lobos" Master station failed before the baseline testing was run. Thus it was not possible to confirm the error estimates derived from analysis of the cruise data with independent baseline measurements.

II. DESCRIPTION

A. MINI-RANGER SYSTEM

The Motorola Mini-Ranger system being used by MBARI and NPS is the Falcon 484. It is widely used for precise positioning in a variety of nearshore marine applications like hydrographic surveying, dredging, oceanographic data collection, etc. Numerous excellent descriptions of the system are avaliable in the literature.

The system operates on the principle of a pulse coded transponder. The Master station (also refered as to as the Receiver-Transmitter) is located on the ship and ranges to a maximum of four Reference stations ashore. The maximum update rate is once per second. The Master and Reference stations transmit on different frequencies in the microwave band, 5570 and 5480 Mhz, respectively. Both range and signal strength data are output for each Reference station interrogated.

Signal strengths are computed at the Master as a relative indication of the power level received from the Reference station. Values can vary from about 5 to 99. The manufacturer warns that any ranges with signal strength below 13 are "weak" signals, subject to random errors exceeding the 2 meters (1 σ) specification. Signal strength obviously falls off with increasing range, but can also drop due to any degradation of propagation conditions between the ship and shore station. Hence, weak signals can and do occur at any range. Monitoring of the received signal strength is critical to assessing the accuracy of all range data.

The range is computed at the Master station based on the measured round-trip travel time for the pulse and a preset refractive index for microwave propagation in the atmosphere. Unless changed by the user, the receiver assumes a value of $N=(n-1)x10^6=320$ as an indicator for the refractive index (n), which is the value used throughout this study. Output ranges also can be corrected for any constant (systematic) error previously entered by the user. Because this constant error includes time delays at both ends of the line, it is essential to have a specific

calibration of each Master/Reference station pair. The manufacturer notes that without calibration, systematic range errors of up to ten meters are possible.

It is possible to have the receiver correct ranges from "slope to horizontal" distances before output, based upon user provided elevations of the Master and Reference stations. During this study, both the MBARI and NPS equipment were configured to output "slope" ranges only, choosing to handle this correction as part of the position computation algorithm.

The Reference stations are supplied with electric current of 22 to 32 Volts DC from a pair of common car batteries, or permanently from an AC supply through a converter. A possible insufficient current supply can cause errors in the displayed distance in the receiver [Mini-Ranger Operation Manual, p.II-11].

The standard system has a maximum range of 37 km (20 n.m), with Reference station antennas of 13 db. The maximum range can be extented to 75 km (40 n.m) by raising the antenna gain of the Reference stations to 19 db, if the station's elevation is sufficient (due to the dip of the horizon). The master station, which is on the vessel, has an omni directional antenna of 6 db. The discussion and results in this thesis are all given using extended (19 db) gain antennas on the shore stations.

Another significant factor for a Reference station is the directivity of its antenna. The given maximum range of the system corresponds to the main lobe direction and drops as one moves to the sides. Figure 1 shows the pattern of a 19 db gain antenna of a shore station. We can see that the range drops under 30 km at 40° off the center direction. This is significant for a station that uses its maximum range ability and thus makes the choise of antenna directivity critical.

B. MONTEREY BAY NETWORK DESCRIPTION

The Motorola Mini-Ranger network in Monterey Bay consists of 6 stations with high gain antennas (19 db), installed permanently on known positions around the Bay. The installation was done by both MBARI and NPS serving primarily the Biological and Oceanographic research of their vessels "Point Lobos" and "Point Sur" respectively. The positions at which the stations are in-

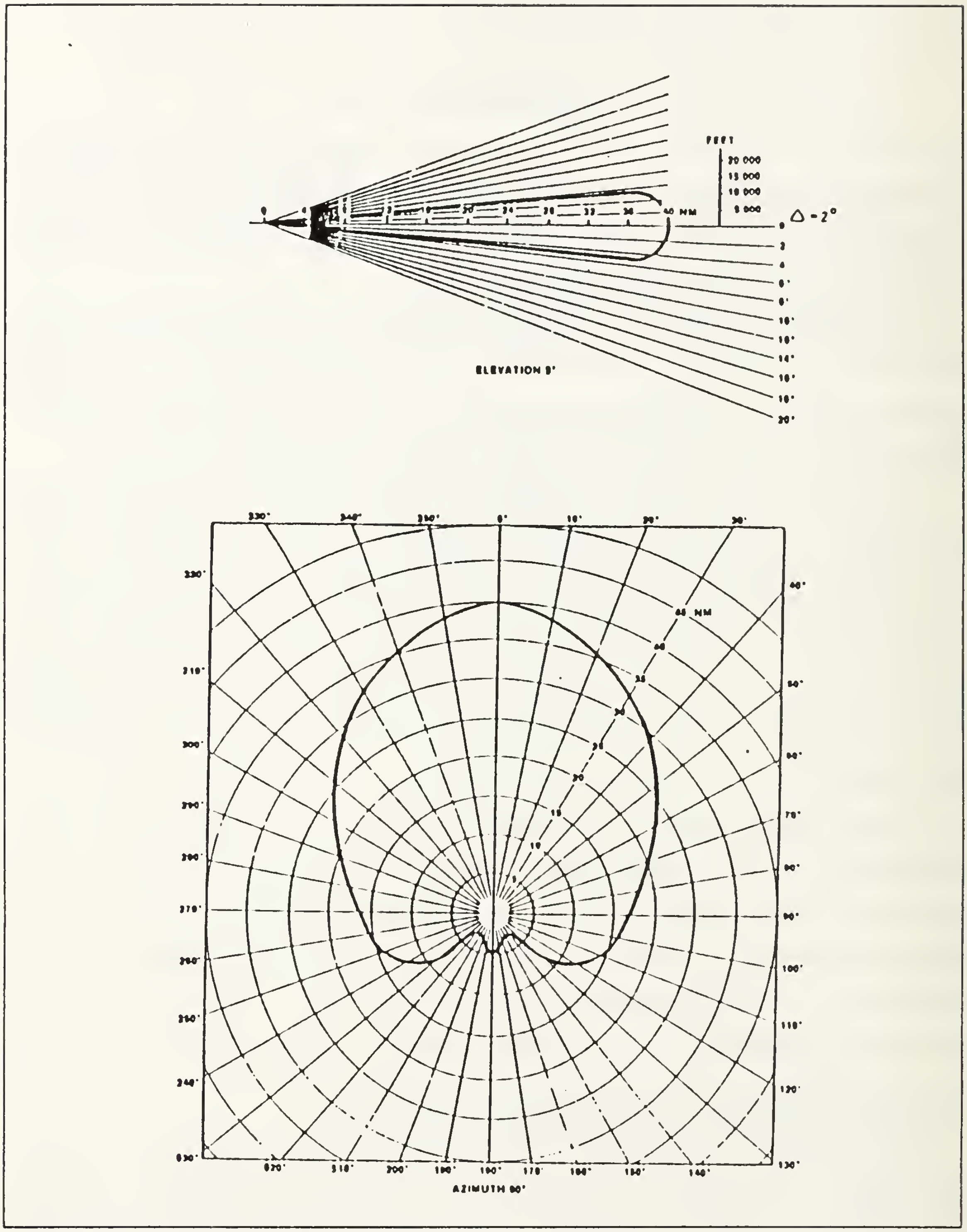

Figure 1. 19-db ANTENNA PATTERNS.

Table 1. PRELIMINARY POSITIONS OF THE MINI-RANGER STATIONS

Name	Latitude(N) Longitude(W) deg min sec	UTM coordinates	Scale factor	Elevation (m)
Trevor	36 58 28.785 122 02 31.536	585260.161 4092490.284	.999690	51.7
Wats	36 54 26.895 121 50 39.819	602947.672 4085231.399	.999731	23.1
Packard	36 49 44.407 121 46 04.912	609863.128 4076611.345	.999749	33.9
Hays	36 38 33.826 121 47 45.895	607621.289 4055915.264	.999743	137.2
Doppler	36 36 05.601 121 52 37.479	600434.009 4051260.014	.999724	10.0
Hank	36 36 25.381 121 55 08.722	596669.490 4051826.411	.999715	134.5

stalled are not ideal due both to the permanent power supply problem and to the fact that some of the ideal station positions are on private properties.

On board the "Point Lobos" the Mini-Ranger omni-directional antenna was installed on the mast 9.1 meters above the water level. Thus the maximum achievable range due to the line of sight effect was increased.

The shores of the Bay and the nearshore areas are generally low sand dunes so some stations don't have the proper altitude to reach their maximum range.

Table 1 gives the preliminary positions [Schnebele, 1989] of the stations, the UTM grid coordinates and their scale factor. The horizontal datum is the American Datum of 1983 (NAD 83). The UTM projection used is for Zone 10 (central meridian 123° W.) and the scale factor 0.9996. Any errors in the posi-

tions of these stations will propagate into the computed vessel position by an amount that depends on the geometry. If the errors are smaller than several decimeters then there is no significant effect. Revised positions are shown in Table 3, section IV-C.

The stations are not ideally positioned and so may be moved to different positions in the future to allow better coverage of the areas of interest.

Station Doppler is not yet permanently installed for safety reasons.

III. THEORETICAL APPROACH TO THE PROBLEM

A. THE RANGING PROBLEM

The technique used for computing the ship's position using ranges from known reference stations will be derived and explained in the beginning so the reader will be able to follow and understand the data manipulation and results of this study. It's well known that one way to handle the computations involving ranging data is to work on some appropriate projection (e.g the UTM projection). There are several techniques that can be used for the position derivation:

- Averaging the coordinates resulting from all possible combinations of measured ranges.
- Position calculation using the two most accurate ranges (using of the rest as a check).
- Graphical methods.

In this thesis we use the variation of coordinates method which is described in Cross [1981]. For the position derivation, at least 2 ranges are needed (two unknown parameters in the plane solution X,Y). With more ranges one can estimate the accuracy of the resulting position and also make statistical decisions about the quality of the data.

Figure 2 illustrates the concept of ranging from the i-th station. Consider a station S_i in a coordinate system XY. The observed range, reduced to the plane, is OR_i (not shown). Consider an assumed position (AP). The distance between the reference station and the assumed position is CR_i. The calculation of the values dX,dY, which represent the corrections that have to be applied on the AP, will give the desired true position (TP) after some iterations.

As is obvious from the figure:

$$(X_i)_{AP} = X_{AP} - X_{Si}$$

$$(Y_i)_{AP} = Y_{AP} - Y_{Si}$$

The key equation is the one for the calculated range:

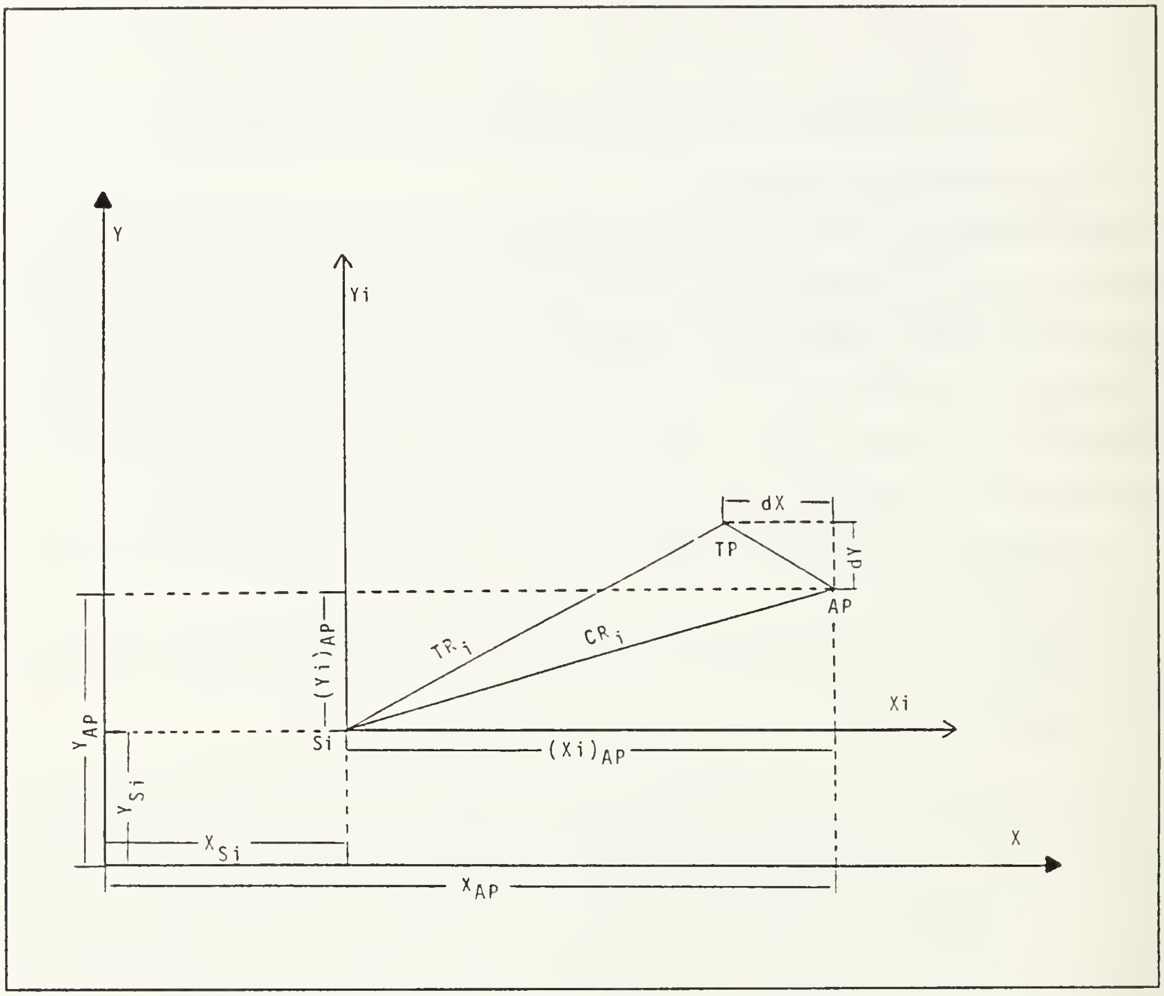

Figure 2. VARIATION OF COORDINATES METHOD

$$(CR_i)^2 = (X_i)^2_{AP} + (Y_i)^2_{AP}$$

In order to find the transformation from range coordinates to position coordinates it is necessary to find the derivative:

$$2CR_i dCR_i = 2(X_i)_{AP} dX + 2(Y_i)_{AP} dY$$

$$dCR_i = MdX + NdY$$

where

$$M_i = \frac{(X_i)_{AP}}{CR_i}\, dX$$

$$N_i = \frac{(Y_i)_{AP}}{CR_i}\, dY$$

The estimate of the true range then is equal to the observed range plus an error which can be positive or negative, called the residual V_i. It is also equal to the calculated range plus the increment dCR_i.

The true range then is $OR_i + V_i$ where V_i is the residual. But it's also $CR_i + dCR_i$. Solving for dCR_i, we take:

$$dCR_i = (OR - CR)_i + V_i$$

and finally:

$$M_i dX + N_i dY = (OR - CR)_i + V_i$$

For the n ranges problem, in matrix form, the equation may be stated as follows:

$$AX = B + V$$

Where matrices A ,B and X respectively are:

$$A = \begin{bmatrix} M_1 & N_1 \\ M_2 & N_2 \\ \vdots & \vdots \\ M_n & N_n \end{bmatrix}$$

$$B = \begin{bmatrix} (OR - CR)_1 \\ (OR - CR)_2 \\ \vdots \\ (OR - CR)_n \end{bmatrix}$$

$$X = \begin{bmatrix} dX \\ dY \end{bmatrix}$$

The standard solution for this formulation using the least squares method (Bomford, 1980) gives:

$$X_a = (A^T WA)^{-1} A^T WB$$

$$V_a = AX_a - B$$

Where the subscript a indicates that the value is approximate. The best solution is obtained by iterating until X converges to less than some limit.

W is the weight matrix. The standard daviation σ_i of a range measurement is an expresion of its accuracy. It is standard to weight the range measurements using $\frac{1}{\sigma_i^2}$ which ensures achieving the minimum variance solution [Hamilton, 1964].

Assuming that there is no correlation between measurements, the weight matrix becomes diagonal as follows:

$$W = \begin{bmatrix} 1/\sigma_1^2 & 0 & \cdot & \cdot & 0 \\ 0 & 1/\sigma_2^2 & \cdot & \cdot & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & \cdot & \cdot & 1/\sigma_n^2 \end{bmatrix}$$

Motorola estimates the standard deviation (1 σ) of a single range measurement to be 2 meters. The individual user has to set his own estimated (σ) for his equipment (see section IV-H).

The unbiased estimate of the variance-covariance matrix of the adjusted position is given by

$$\Sigma_x = \sigma_o^2 (A^T WA)^{-1}$$

This matrix includes the variances and the covariances in the coordinate system we use (X,Y coordinates) and appears as follows:

$$\Sigma_x = \begin{bmatrix} \sigma_x^2 & \sigma_{xy} \\ \sigma_{xy} & \sigma_y^2 \end{bmatrix} \tag{18}$$

Assuming that $\sigma_i = 2m$, then the combination of two ranges can result in positional error of 7.8 m (drms) in the limiting case of 30° intersection angle. Drms is derived from the unbiased estimate of the variance covariance matrix as follows:

$$1 drms = \sqrt{(\sigma_x^2 + \sigma_y^2)}$$

This error of 7.8 m can be larger when the system is not calibrated. For uncalibrated systems the error of a single measurement can exceed 10 m [Motorola Mini-Ranger manual].

The quantity σ_o^2 is the a posteriori variance of unit weight. It can be computed as follows:

$$\sigma_o^2 = \frac{(V_a^T W V_a)}{dof}$$

Where dof is the degree of freedom, or n-2 when solving for X,Y position coordinates using n ranges. Ideally, σ_o^2 should equal unity.

According to Cross [1981], when the degrees of freedom are small it is dangerous to use a single determination of σ_o to judge the quality of the position. It is better to use an average value of σ_o from the whole data set.

But the big question is "how we can say that the value of σ_o is out of bounds? For this question a chi square one or two tailed test is the best indication, even though there are situations where it is not sufficient [Uotila, 1975]. If the test fails, this may be an indication that one or more of the following error sources exist that cause the large value of σ_o.

- Error in the mathematical model involved in the solution (Scale factors, Refractive Index used etc.)
- Computational errors.

- High correlations between observations or very poor geometry of the situation.
- Influence of the omitted higher order terms in Taylor series expansion which can be critical for higher order accuracy systems (primarily when the Master station is far away from to the Reference station).
- Incorrect variance-covariance matrix of the observed quantities. It means that for a non well calibrated system, large values of σ_o are expected.
- Blunders in observations arising from various factors in the measurement process (Multipath, unstable readings, etc).

So if the statistical test used for σ_o shows that something is wrong an investigation is needed for the detection of the possible error source and its elimination from the data.

B. PROPAGATION EFFECTS

The line of sight limitation is one of the critical factors in the network installation. The radius of curvature of the signal path is about 4 times greater than the Earth's curvature, so the heights of the Reference stations and the height of the Master station antenna govern the maximum range of the system, according to the formula, [Motorola Mini-Ranger Manual, 1981]:

$$d = 4.04(\sqrt{h_r} + \sqrt{h_m})$$

Where h_r and h_m are the heights in the Reference and Master stations respectively and d the maximum range in kilometers.

The maximum range of the system can be reduced due to the atmospheric conditions. Attenuation of the signal due to rain is given by [Casey, 1982]:

$$A = ar^b$$

Where A is the attenuation of the signal in db, r is the rainfall rate in mm hr and a,b are frequency functions. For the Miniranger mean frequency (5.5 GHz), their numerical values are a = 1.48×10^{-3} and b = 1.1469.

Another formula is given for fog, based on the water concentration per cubic meter:

$$A = 4.87x10^{-4} M f^2 db/km.$$

Where M is the water content in gr/m^3 and f is the frequency in Ghz.

Table 2 gives the attenuation of the signal for rain and fog, at 5.5 Ghz which is an average operating frequency for the Mini-ranger. In terms of distance, we have 8.0 km range reduction at 40 km for each db drop. So, for example, in a distance of 40 km with heavy rain conditions we have 1.2 db drop in the signal (11.6 km reduction in maximum range). This drop in signal power can introduce unexpected range errors when signal strength drops below the Critical Strength Threshold (CST).

Table 2. ATTENUATION OF THE SIGNAL AT 5.5 MHZ

Precipitation Rate (mm/hr)	Attenuation (db/km).	Fog (gr/m^3)	Attenuation (db/km)
2	0.0015	1.0	0.0147
4 (drizzle)	0.0072	1.2	0.0177
6	0.0116	1.4	0.0206
8	0.0161	1.6	0.0236
10	0.0208	1.8	0.0265
12	0.0256	2.0	0.0295
14	0.0305	2.2	0.0324
16 (heavy)	0.0356	2.4	0.0354
18	0.0407	2.6	0.0383
20	0.0460	2.8	0.0413

A possible problem that can appear in the survey area is the multipath phenomenon of the signal. It can cause constructive or destructive inteference at the

receiver. There exist two types of multipath. The first, vertical multipath is caused by reflection of the signal on the sea surface. The destructive interference at the receiver due to vertical multipath is called "range hole". The second one is the horizontal multipath due to reflection of the signal on walls or other surfaces. The destructive interference of the horizontal multipath is seen as "unstable readings".

Range holes are very important in networks that operate at line of sight and can be a major source of positional problems. The best way to avoid such a problem is to put an additional Mini-Ranger Master station at a different height on the vessel.

The accuracy of the range measurements is affected by the weather conditions (temperature, humidity, pressure). A fixed value of the refractive index (N) is input into the system prior to a survey and kept constant throughout the survey. The default refractive index (N = 320) corresponds to atmospheric conditions of $20°C$, 50% and 1013 mb respectively.

Extreme atmospheric conditions, like high temperature along with either high relative humidity or dry atmosphere, can give rise to large scale errors in the measured distances. For this reason further investigation was done to estimate the magnitute of the atmospherically induced errors (see section IV-E).

C. LOW SIGNAL STRENGTH

Several investigators [e.g Casey, 1982] have shown that range errors, both bias and standard deviation, tend to increase once the received signal strength drops below some critical level. This level, usually refered to as the Critical Signal Threshold (CST), is defined by the users accuracy requirements. Typical choices are between signal strengths of 8 to 18. The Motorola Falcon equipment itself flags signal strengths less than or equal to 13 as potentially suspect.

The signal strength from the shore station is also a factor that can introduce large errors in the range measurements, but it is always output by the system and can be used in subsequent data processing. When signal strength is above the CST limit, the errors have a Gaussian distribution, (mean value zero and relatively small variance). But when the signal strength is below the CST limit the

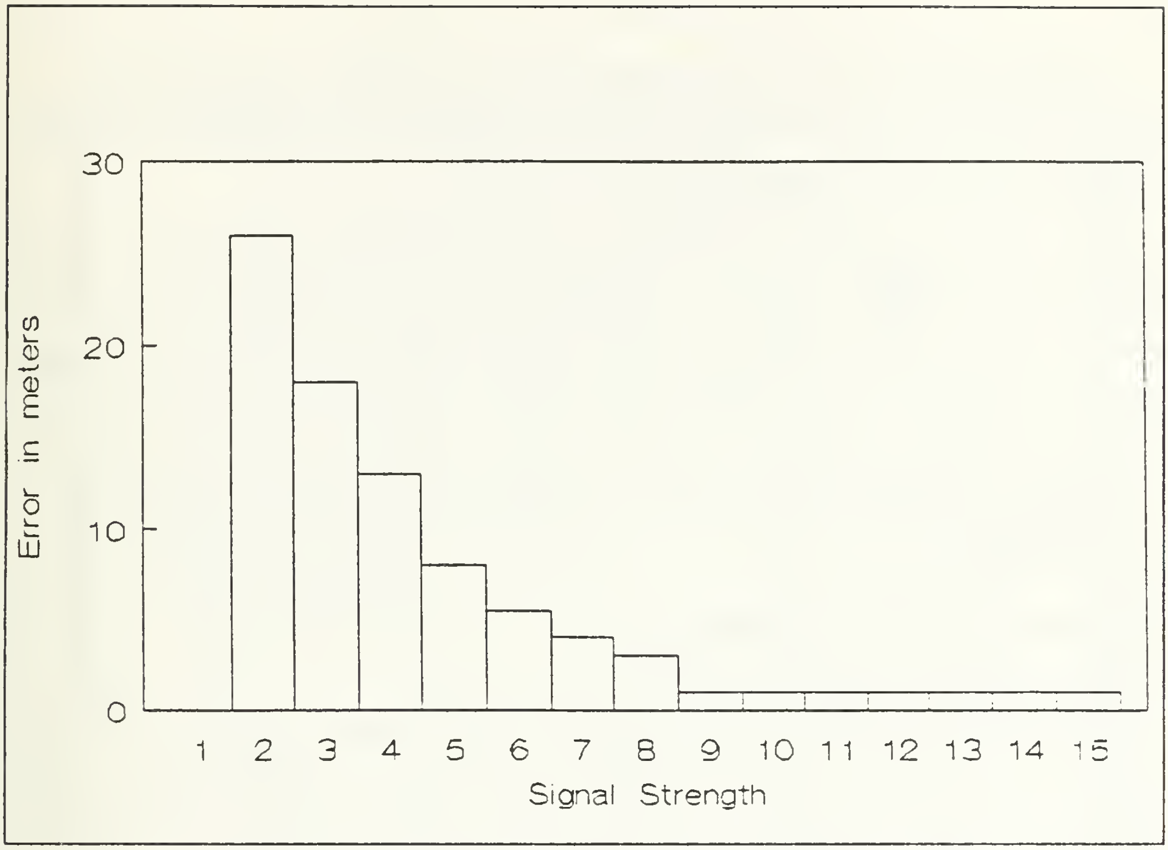

Figure 3. VARIATION OF MEAN ERROR WITH SIGNAL STRENGTH

errors follow a logarithmic curve. That means the range error increases logarithmically as one receives smaller values of signal strength [Casey, 1982].

Figure 3 derived by Casey, gives the CST at SS=8 . For particular applications each user can set his own estimated value for CST in order to either reject the low signal strength meausurements, or to increase the standard deviation of the measurement.

The SS of each signal depends strongly on the distance from the reference station, (it drops with the inverse square of the distance). It can also vary due not only to multipath phenomenon, (as we explained earlier), but also due to the angle to the main lobe direction and the atmospheric conditions.

IV. TESTS ON THE MINI-RANGER NETWORK IN MONTEREY BAY

A. MINI-RANGER CRUISE DATA

On 31 March 1989 the Vessel Point Lobos, from MBARI, sailed for a trip in Monterey Bay to make trials and calibration on the Mini-Ranger stations. The Master station was installed on the mast at height 10 m above the water. During this trip useful data were collected and position estimates calculated. This data was processed in a preliminary fashion in order to detect possible error sources.

Figure 4 shows the routes of the vessel followed. A division of the Bay into smaller areas was used, (as shown on the figure), in order to subdivide the data for processing and error analysis purposes. The division was based on the concept of nearshore and open bay regions.

Another trip was subsequently done for NPS research purposes on 22 September 1989, and some more data collected as shown on the same figure. The master station for this cruise was different and the data w collected under different conditions of atmosphere, time and instrumentation. It was considered possible that the positional results from these two data sets may vary in accuracy.

First we examined the earlier data set of MBARI, which already had the positions and their statistics calculated. We were informed by MBARI that for the position derivation they used the method of variation of coordinates. No details on the specific code in this software were avaliable.

The first step was a general view on the residuals and the "standard deviation" provided in MBARI's data of the whole trip. This showed that something did not work well when the vessel was nearshore , especially in the SW portion of the Bay. Figure 5 shows the areas of the greater and more variable standard deviation of the data set. In general as shown in Figure 5, areas E and G have fewer problems. It was not obvious which station or stations combination was responsible for the big residuals.

Another problem was the variation of signal strength and its unexpectedly high values. In many portions of the data set, the signal strength was much higher

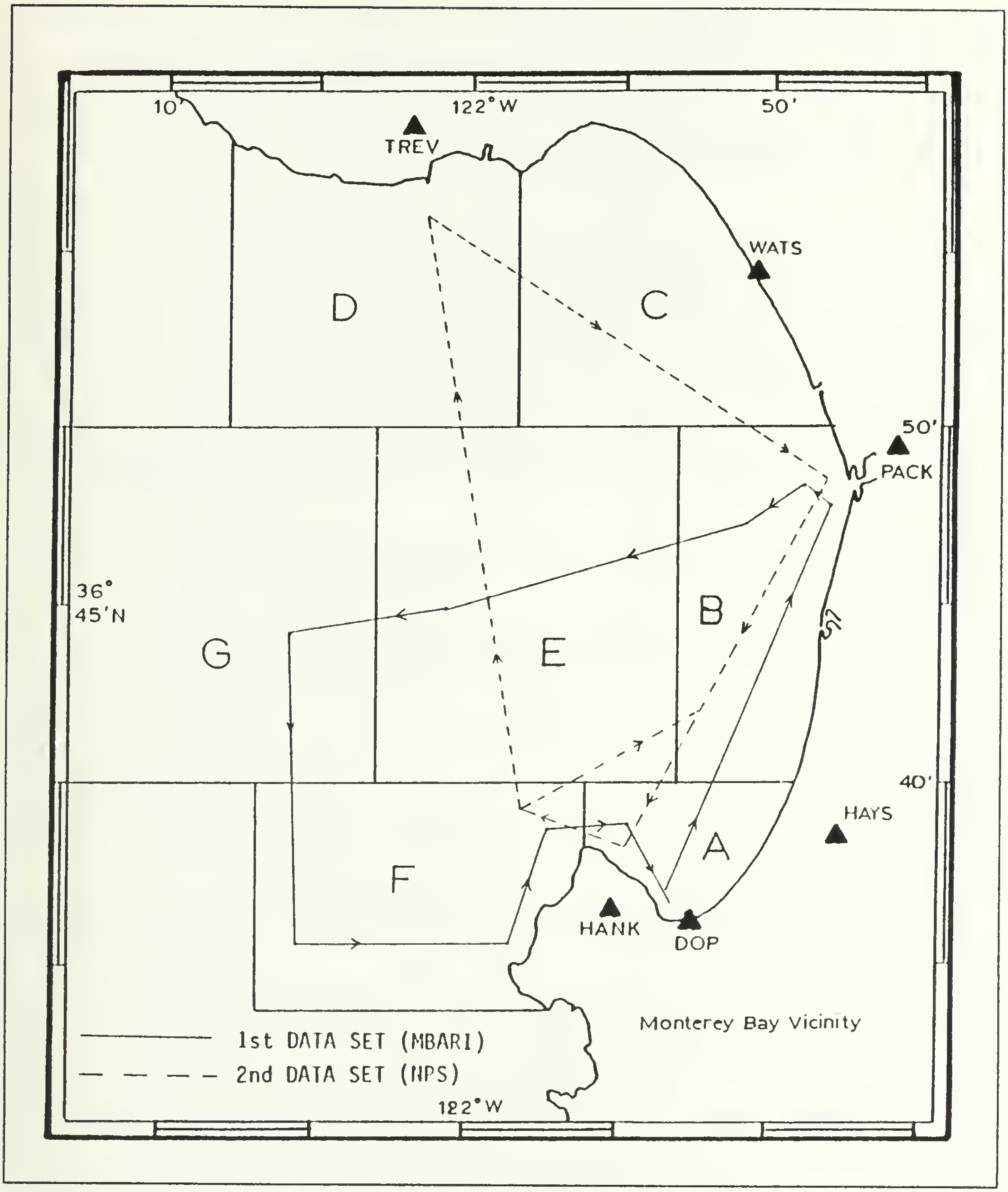

Figure 4. SHIP ROUTES FOR THE TWO DATA SETS/AREA DIVISION

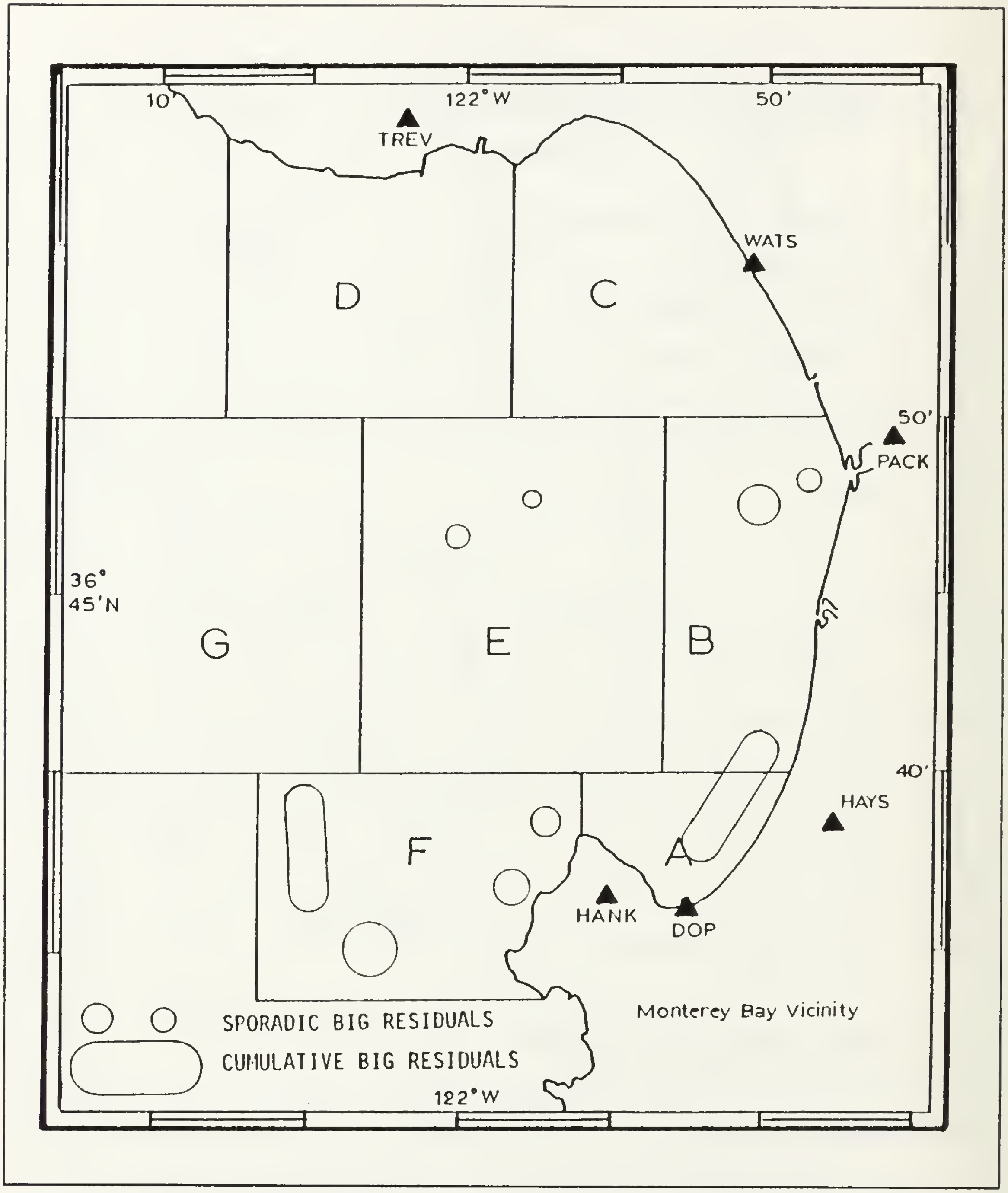

Figure 5. AREAS OF GREATER STANDARD DEVIATION

than expected for such a range. The appearance of signal strengths greater than 70 in distances more than 10000 meters is unusual. This is a strong indication of possible system malfunction.

Because the data set did not show the expected accuracy, the following series of tests and checks were performed:

- A visit to the stations for inspection of directional limitations, antenna installation problems and other possible affecting factors.
- A check of the station positions with geodetic survey techniques, (triangulation, traverse, or differential GPS), and a least squares adjustment of the survey data with fixed geodetic control points around the Bay.
- Check of the software used for the position derivation using the variation of coordinates algorithm with accurate grid scale and slope distance correction techniques.
- A theoretical view of the geometrical accuracies with the use of various station combinations in the Bay area.
- A check on the effects of extreme meteorological conditions to check for the possibility of introducing range errors in excess of 1 meter.
- A range hole prediction for the network.
- An investigation into the possibility of correcting those ranges with signal strengths below the CST.
- A calibration test for determining biased or linearly varying errors and their variability with signal strength above the CST.

B. INSTALLATION CHECK AND ANTENNA DIRECTIVITIES

On 20th of July, a visit to the stations TREVOR, WATS and PACKARD was done for visual examination, check on the antenna directivity , possible signal blocking from nearby obstructions and other possible affecting factors. The stations HAYS and HANK were visited on the 1st of August and 25th of September respectively. The alignments of the antennas were determined to approximately 2° using a small portable magnetic compass. All the magnetic bearings are given as true bearings. A short description is given below for each station and a map is presented (Figure 6) for clarification:

- TREVOR: This station is installed on the roof of a house in Santa Cruz. The antenna is attached to the chimney of the house and is oriented towards 175°. The signal is blocked by a rocky hill from 215° to approximately 100°

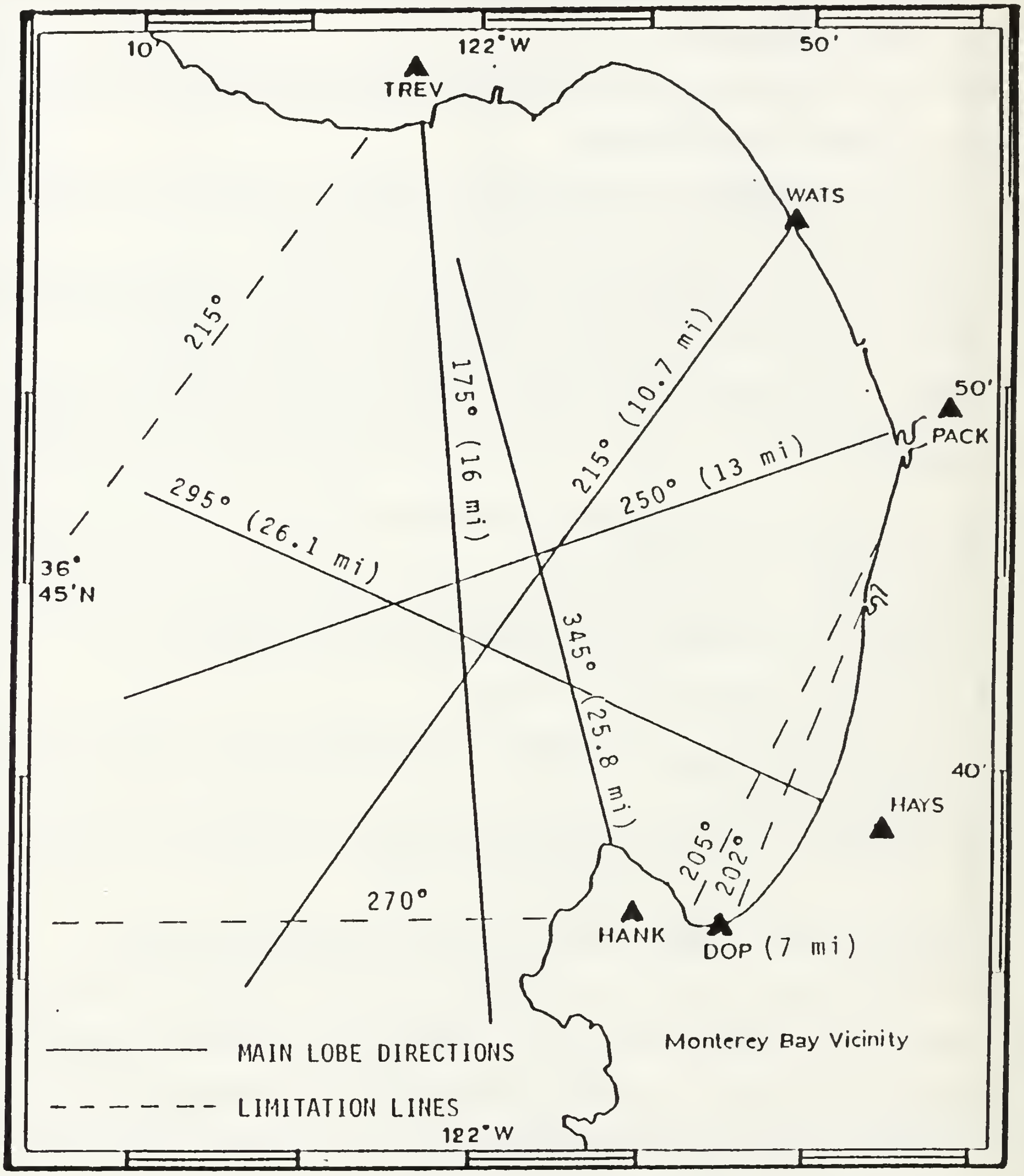

Figure 6. OBSERVED ANTENNA DIRECTIVITIES OF MINI-RANGER NETWORK IN MONTEREY BAY

(clockwise). There is no clear view of the Northern near shore Bay region but this area is of little interest.

- PACKARD: Installed on the roof of a wood craft building, hooked on a thin mast, on private property between Watsonville and Moss Landing. Its antenna points to 250° and may be blocked by the Moss Landing electric plant stacks between 202° and 205° There were no other problems observed for this station.
- WATS: Installed on the roof of a commercial building near the beach at Watsonville. Its antenna points at 215° .The entire Bay area is unobstructed. The antenna is approximately 2 feet from the vertical wall of the building.
- HAYS: Installed on the roof of Silas B. Hays hospital at Fort Ord with an uninterupted Bay view and directivity of its antenna to 295° . The perfect view along with the height of the station makes it useful in some portions SW of Point Pinos . The signal is blocked from the higher Pacific Grove hills from 253° back to the South.
- HANK: Installed on the roof of a house in Pacific Grove. While it has good height the signal cannot reach the nearshore portion from Point Pinos to Monterey harbour due to high trees existing downhill. The directivity of its antenna is 345° and the signal may been blocked by high trees from 005° to 035°. The station is offset from the position specified by the preliminary coordinates. This particular correction is given in the discussion in section C below.
- DOPPLER: This station was installed near NPS Beach Lab. but due to safety reasons was subsequenly removed.

It was not possible to check the electric current supply of the stations, but a voltage stabilizer can help the system to be kept healthier and unstable outputs can be avoided in the future.

C. POSITION CHECK

Geographic coordinates for the station sites had been determined on the North American Datum of 1983 (NAD 83) by geodetic survey techniques, with ties to existing horizontal control points published by the National Geodetic Survey [Schnebele, 1989]. Conventional ground survey and Global Positioning System (GPS) techniques were both used. The survey data had been analyzed with a three-dimentional least-squares adjustment software package (GEOLAB, by GEOSurv. Inc.). Absolute horizontal position accuracies estimated by the adjustment were better than 8 cm (circular error, 95% confidence level). Additional work to confirm the offset positions of the Mini-Ranger units at PACKARD and

WATS, has yet to be completed, but is not expected to shift their preliminary positions by more than a few centimeters at most.

These station coordinates were converted to Universal Transverse Mercator grid coordinates (UTM Zone 10) for use in the vessel position computation algorithms. The UTM system has been adopted as the standard grid used by MBARI and NPS with this network. The specific Transverse Mercator Projection algorithm [Floyd, 1985] is accurate to within 1 cm for the entire zone.

As described earlier, station HANK was offset from the preliminary position. The offset was measured by a simple magnetic compass for azimuth and a tape for distance and should have errors no greater than 5 cm. The measured bearing was 066° true and the distance 41 inches. The two positions were at the same height, so the corrections in UTM are: dx = 0.952, dy = 0.424, dz = 0.00 in meters.

The results are sumarized and the revised station positions provided in the Table 3. With the exception of station HANK, the revised positions of the stations differ by less than 10 cm from the preliminary positions. It is concluded that the station positions are not the source of the observed inaccuracies.

D. ESTIMATION AND COMPARISON OF DERIVED POSITIONS

1. Development of position derivation algorithm

The measured ranges were used to recompute the ship's positions by the method of variation of coordinates [Cross, 1981]. These recomputed positions were then compared with those provided by MBARI. The comparisons showed that there is a discrepancy between the given positions and the recomputed positions on the first data set, which in some cases were significant. Because of these discrepancies, we ignored all the given MBARI positions and recomputed all their data.

For this purpose, a program was written in Turbo Basic. This program uses the variation of coordinates method on the UTM projection surface. Scale factors were computed for each line. The program is given in the Appendix 1 and can be followed by comments provided in the code.

The measured distances from the system, for each case, are corrected for their slope with the assumption of a right triangle (ignoring the curvature of the

Table 3. REVISED POSITIONS OF MINI-RANGER STATIONS

Name	Latitude(N) Longitude(W) deg min sec	UTM coordinates	Elevation
Trevor	36 58 28.785 122 02 31.536	585260.158 4092490.287	51.1
Wats	36 54 26.896 121 50 39.821	602947.636 4085231.429	22.6
Packard	36 49 44.404 121 46 04.911	609863.147 4076611.241	33.4
Hays	36 38 33.824 121 47 45.894	607621.298 4055915.205	136.7
Hank	36 36 25.393 121 55 08.683	596670.450 4051826.796	134.1

Earth). This assumption inserts an error of 4 to 5 cm at the extreme ranges which is insignificant for Mini-ranger measurements in the areas covered by the network. but it makes the calculations simpler. For the complete correction one can look in chapter 15 of Laurila [1981].

The next correction that was made to the measured distances was for the scale factor of the UTM projection. The following formula computes the scale factor for the line between the Master and each Reference station:

$$m = m_o(1 + \frac{E_u^2}{6R^2})$$

Where m is the required scale factor, m_o is the scale at the central meridian (0.9996), R is the mean radius of the Earth (6375 km) and E_μ is the mean Easting value for each case. The mean Easting value is derived from the formula:

$$E_\mu^2 = E_1^2 + E_1 E_2 + E_2^2$$

Where E_1 and E_2 are the true Eastings ($x_i - 500000$), of the Master and the Reference stations respectively. The formula is a simplification of the one given by Bomford [1980, p193] and the error due to this is of millimeter order, which for our purposes is negligible.

The outputs of the program are the least squares estimate for the position of the vessel, the variance covariance matrix Σ_x, the residual vector (V) and the a posteriori variance of unit weight $\hat{\sigma}_o^2$. Measurements were assumed independent so the diagonal weight matrix is treated as a vector in the calculations.

The a posteriori variance of unit weight $\hat{\sigma}_o^2$ is the one that is used for assessing both the accuracy of the network and the ranging data. $\hat{\sigma}_o^2$ can be scaled as is well known, by increasing the standard deviation of a single range measurement. The resulting $\hat{\sigma}_o^2$ is examined statistically with the chi squared, two tailed test, at a 95% confidence level. The null hypothesis, $\sigma_o^2 = 1$, was tested against the alternative $\sigma_o^2 \neq 1$. When the null hypothesis is accepted, it is an indication, assuming no data blunders, that the system works within the specifications provided by the manufacturers. When the null hypothesis is rejected several possible reasons for this exist. These were summarized in section III-A.

It also should be noted, however, that the presence of any unresolved systematic effects tends to invalidate this type of test. One potential source, not modelled in the position computation algorithm, involves the non-simultaneity of range measurements on a moving ship. In effect, the antenna is not stationary over a cycle of range measurements to all Reference stations. Given each range measurement takes about 55 milliseconds, four range measurements may be spread over a period of about 0.15 seconds. At a nominal vessel speed of 6 knots, the possible error is about 0.45 cm, which is of little importance in this analysis.

Additional error can be inserted due to mast motion. In rough sea conditions the error is big enough (more than 1 meter) and it has to be taken into account by increasing the estimated standard deviation of the range measurements.

2. First data set

The results of the chi square test at a 95% confidence level using standard deviations of 2 and 3 meters on the measured ranges respectively, appear in Table 4.

The acceptable values of $\hat{\sigma}_o^2$ under these conditions are:

For three ranges $0.00 < \sigma_o^2 < 5.024$

For four ranges $0.025 < \sigma_o^2 < 3.69$

The numbers given in the first two columns of Table 4 represent the percentage of the number of positions for which the null hypothesis was rejected against the total number of the positions examined. The number provided does not include some abnormaly high a posteriori variances of unit weight which were caused by multipath effects, or low SS. These data were rejected as blunders. Their percentage appears in the last column.

As can be seen, even when $\sigma = 3$m, the number of rejections is clearly much higher than the 5% which one would normally expect.

In the column 'Difference' we can see how many of the positions that were rejected when $\sigma = 2$m, are accepted with $\sigma = 3$m. This is an indication either of poor calibration of the system or that the system does not perform to the standard claimed by the manufacturer. It should be noted that the range data had been corrected for an estimate of systematic errors determined in a prior calibration.

The results shown in Table 4 suggest the possibility that the master station used may have beeen poorly calibrated. For this reason, an examination of the distribution of the residuals for each reference station was undertaken. After examining the distribution of the range residuals for each reference station, it became clear that some stations were consistently biasing the position solutions. From the distribution of these residuals, the bias was estimated by comparing their mean, median and most probable values. The mean residuals and the

Table 4. REJECTED PERCENTAGE WITHOUT REVISED CORRECTORS

AREA	$\sigma = 2$	$\sigma = 3$	Difference	Rejected blunders
A	68%	48%	20%	11%
B	82%	37%	45%	9%
E	69%	22%	47%	25%
F	27%	13%	14%	33%
G	43%	27%	16%	29%

adopted correctors are shown in Table 5. This simple averaging of observed residuals is not an ideal procedure for estimating bias errors. The least-squares process tends to redistribute an error in any one range to errors (residuals) in all ranges. Recognizing this limitation, however, the procedure gives a useful estimate of uncorrected bias errors.

The results for the corrected data are shown in Table 6 and can be directly compared with Table 4. The improvement as we see is above 65 %.

In the column 'Difference' we can see, in comparison with the one of table 4, that the values are much lower, which is an indication that most of the calibration uncertainty has been removed.

Even after this procedure, some a posteriori variances of unit weight are still high, especially in areas A and B. The possible reasons for this can be:

- Incomplete removal of the blunders.
- Operation of some stations at low SS which in turn causes larger deviations from the normal values.
- Incomplete removal of the bias errors described above. The technique used does not eliminate the entire error, but only estimates it.
- For any one of a number of reasons the signal can be lost temporarily. When it is regained it sometimes lacks stability for several readings.

Table 5. MEAN RESIDUAL AND VALUES USED FOR RANGE CORRECTORS

STATIONS	Mean residual	Used corrector
Trevor	3.91 m	-3.5 m
Wats	-1.66 m	1.5 m
Packard	-0.24 m	0.0 m
Hays	2.61 m	-2.5 m
Doppler	3.64 m	-3.5 m
Hank	-0.24 m	0.0 m

Table 6. REJECTED PERCENTAGE AND IMPROVEMENT WITH REVISED CORRECTORS

AREA	$\sigma = 2$	$\sigma = 3$	Difference	Improvement
A	38%	22%	16%	44%
B	31%	14%	17%	62 %
E	14%	06%	8%	79 %
F	8%	0%	8%	70%
G	13%	7%	6%	69%

- Higher value of the standard deviation of the system used than the one used for the weight matrix formation.

3. Second data set

The second data set was examined statistically in the same way and the results appear in Table 7. We can see that the second data set gives much better solutions. This was expected because it was known that the master station used for this data collection, was well calibrated.

Table 7. REJECTED PERCENTAGE FOR THE SECOND DATA SET

AREA	Rejected percentage for $\sigma = 2$
A	9%
B	6%
C	6%
D	7%
E	7%
F	7%

The previous data set, for reasons noted earlier, showed major problems when the ship was in areas A and B. The second data set, however, shows consistent results in all areas and a low rejection percentage even when $\sigma = 2$m. These results suggest that the standard deviation of the range measurement should be between 2 and 3 meters.

E. GEOMETRICAL ACCURACIES

The position quality given from the Mini-ranger network in Monterey Bay depends strongly on the relative geometry of the ship and the reference stations. The geometric position quality can be represented in terms of error ellipses, confidence circles, or with several other appropriate techniques. When several stations are used, computer techniques are necessary if detailed analysis is to be undertaken. Such techniques are described in Perugini [1988].

The provided figures in Appendix 2 were taken from computer calculations using software associated with MBARI's Navigation processor. The numbers provided represent the semi-major axis of the predicted error ellipse at 95% confidence level that is formed at the particular position, assuming the standard deviation of a single range measurement is 3 meters.

The best working combination appears in Figure 7 and is obtained using stations TREVOR, PACKARD, HAYES and HANK. We can see that the geometry of the position is very good with two combinations of only three stations, i.e; station combinations TREVOR, PACKARD, HANK and TREVOR, PACKARD, HAYES (see Appendix 2)

As is easily seen, station TREVOR occupies a position that gives strong geometry in the mid-Bay regions and its position is the most critical for the network. On the North side of Monterey Bay there are also other higher positions on which a permanent station could be installed with a much better view of the Bay. Most of them are in the University of California Santa Cruz campus and some arrangments have to be made.

In the Watsonville area the hills over Buena Vista Point have a good Bay view but the problem of a permanent electrical supply and security has to be solved. Such a position would overcome the height problem of the WATS station while maintaining its geometry.

Stations PACKARD and HAYS are at the highest elevations in their areas. There is no advantage to shifting their positions without deteriorating the geometry.

Station DOPPLER does not add much to the geometric quality of the network in the mid-Bay but can be used for positioning near Monterey harbor where signals from PACKARD and HANK are obstructed. It also could be shifted NW of Point Pinos on the lighthouse or on another high position to improve the geometry in the Monterey canyon area. Further investigation on this station has to be done for the best choice of a permanent position.

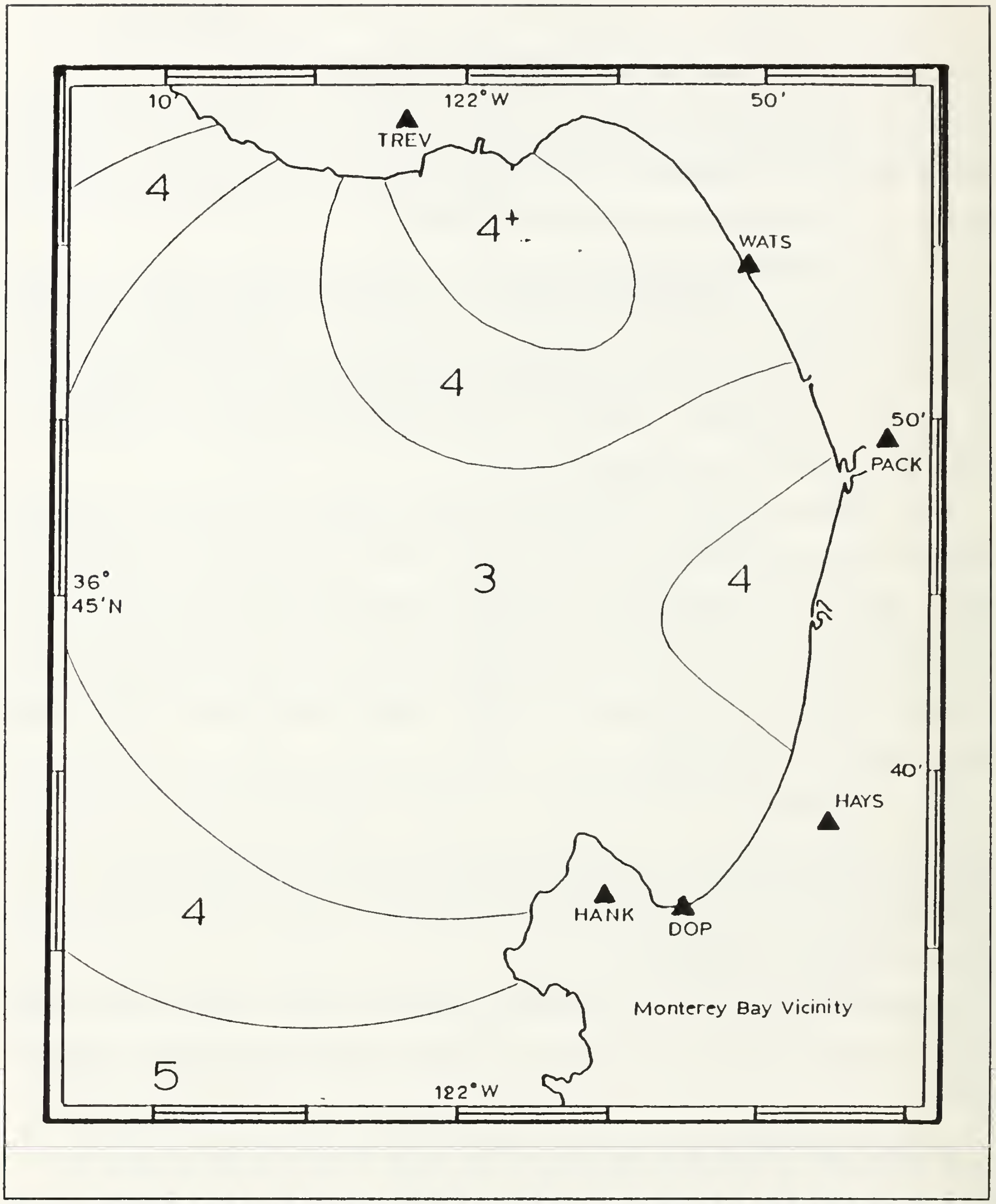

Figure 7. BEST WORKING COMBINATION OF THE MINI-RANGER STATIONS

Station HANK gives very good geometry but its position has some limitations because of obstructions to its Bay view. Some station at the southern site of the Bay is necessary to maintain a good network geometry for the areas of interest.

Generally we can say that the geometry of the network is not responsible for the big standard deviations observed in most regions around the Bay, but it becomes more important as one moves offshore near the Northen and Southern regions.

F. ATMOSPHERIC CONDITION EFFECT OF THE AREA ON THE MICROWAVE PROPAGATION VELOCITY

An investigation was carried out to see the maximum possible error due to propagation velocity which could occur under extreme atmospheric Bay conditions as compared with mean Bay conditions. The atmospheric formulation is described in Chapter 6 p.133 of Laurila [1981]. The effects of temperature (T), pressure (P) and humidity (E) on the refractive index (N) are given from the Essen formula:

$$N = 77.62\frac{P}{T} - \left(\frac{12.92}{T} - 37.19\frac{10}{T}\right)E$$

Where P and E are in mb and T is the dry bulb temperature in K^{o}. But

$$E = \frac{(RH)E_d}{100}$$

Where RH is the relative humidity (%) and E_d is the saturation vapor pressure, given in mb, at the dry bulb temperature. E_d is a logarithmic function of temperature so the effect on the refractive index depends on the temperature and the relative humidity as shown in Figure 8, for various relative humidities and constant atmospheric pressure at 1013 mb.

Daily weather logs, kept by the Meteorology Department of the NPS, were searched for the maxima and minima of temperature and relative humidity in Monterey during 1988-89. This was done so as to compute the average variability of the refractive index and the possible error in distance that is introduced for the

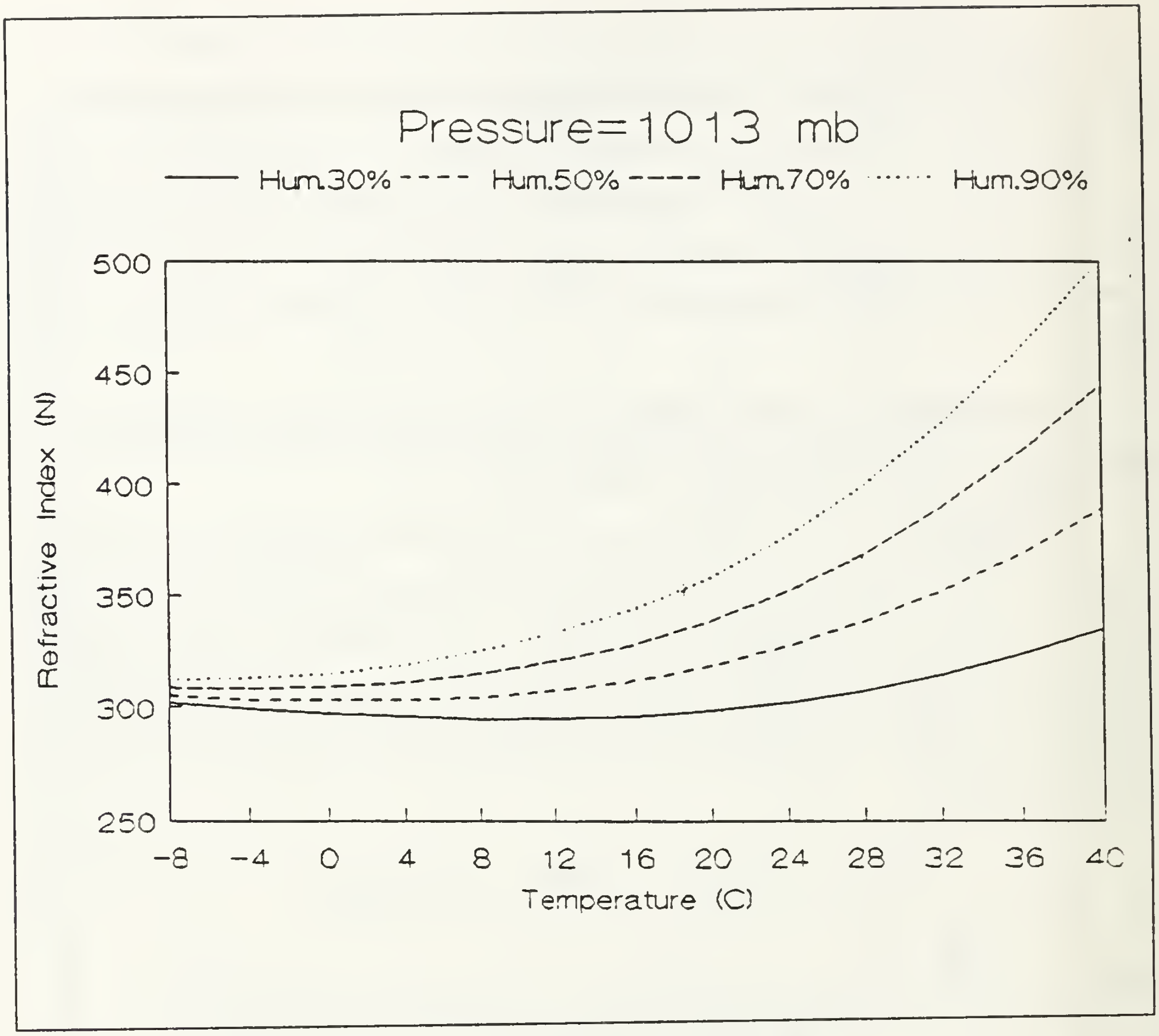

Figure 8. VARIATION OF THE REFRACTIVE INDEX

actual atmospheric conditions. The base for the comparison is the refractive index value (N = 320) that is used from the Mini-ranger for the range calculation.

In Monterey Bay during the spring, temperature averages about 55 $^{\circ}F$ and humidity varies from 30% during the hotest days to 95% during the cold nights. During working hours, a relative humidity of 55% with temperatures 70 F° are usual. Extreme values of 95% RH and 55 $^{\circ}F$ are rare, but if they are accompanied with high atmospheric pressure, 1030 mb, then they give N = 343.6 which in turn corresponds to a distance error of 23.6 ppm. In a possible distance of 40000 m the introduced error is about 1 meter. On the other hand, low atmo-

spheric pressure of 1000 mb with 80 °*F* and 20% humidity, gives N = 288 and 32 ppm error, which in distance terms means 1.28 m at 40000 m measured distance. Average values of N for the spring during working hours are between 310 and 330, which indicates that the assumed Refractive Index of 320 is fair.

During the summer the increased temperature is accompanied with a drop in the relative humidity so the result tends to be the same as in spring with an average N = 320 to 325. The extreme cases here also rarely introduce errors more than 1 meter at distances of 40000 m.

The fall season is the one with a slightly different mean N and more variability. Warm weather with high humidity is more likely to occur. In the extreme cases, at maximum distance, the error could reach 2 meters, but it rarely occurs. The average N = 330 is better to use.

Winter shifts the refractive Index back to the lower values due to the lower temperatures of the atmosphere, which makes the extreme cases more rare. A mean value of N = 315 is better for use.

Generally the resulting error should be less than a meter at extreme ranges and several decimeters on average, when extreme atmospheric conditions happen. Even though the error is small, the use of the seasonal refractive index is advised.

G. RANGE HOLES

Range holes occur due to the vertical multipath, which is caused from reflection of the signal from the sea surface. This is common to all microwave systems that use a line-of-sight propagation path. Figure 9 [Gilb-Weedon, 1976] illustrates the situation.

We count the range holes from the first to the Nth. Here N represents the integer number of wavelengths difference between the direct and the reflected paths. The first range hole occurs at the longer distance from the shore station.

Several factors affect the range hole characteristics:

- The distance between the reference and the master stations. The longer the distance, the wider the range hole zone.
- The height of the stations. The higher the reference stations the fewer the range holes near them.

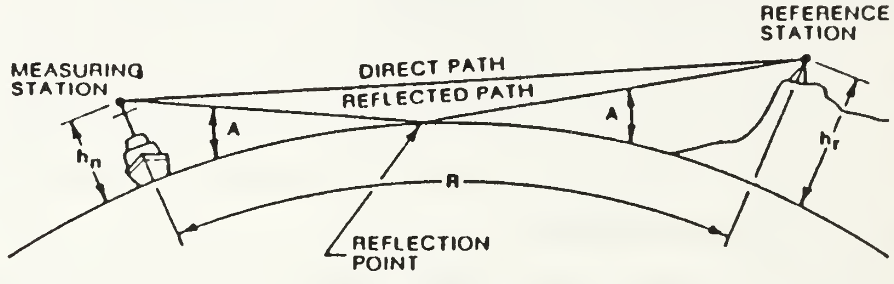

Figure 9. RANGE HOLE OCCURANCE CONCEPT

- The wavelength of the signal. This affects both the width of the range holes, and the distance from the reference station at which they occur.
- The atmospheric conditions along the signal path cause loss of SS. Thus the reflected signal from the sea surface, due to additional losses from the reflection. is too weak to interfere the direct one, when they both arrive to the master station.
- The sea surface roughness. This affects the type of reflection which occurs. In a strongly wave modulated sea, the appearance of the range holes is rare.
- Changes in the sea level due to tides, winds etc., cause range holes to shift location horizontally.

Small reflection angles cause more frequent range holes because the signal has lesser losses in comparison with the case when the reflection angle is bigger. The additional losses of SS, in the second case, weaken the reflected signal which can not then interfere with the direct one.

In reality, the destructive interference is rarely total due to losses of the reflected signal from the sea surface, but it can reduce the SS to below the sensitivity of the receiver or below the CST in the case of Mini-ranger. This will result in signal loss, or worse, in a bigger standard deviation of the measurement.

In the Monterey Bay network, the range hole predictions are shown in Table 8 for each station. For the maximum range of each station we assume a ship antenna of 10 m.

Range holes closer than the third occur rarely because of the bigger angle of incidence which attenuates more of the reflected signal.

Table 8. RANGE HOLE PREDICTION FOR MONTEREY BAY

STATIONS	Maximum range	Range for the first hole	Range for the second hole	Range for the third hole
Trevor	42000 m	18972 m	9486 m	6324 m
Wats	30000 m	8477 m	4238 m	2826 m
Packard	37000 m	12440 m	6220 m	4147 m
Hays	61000 m	50348 m	25174 m	16783 m
Doppler	26000 m	3670 m	1835 m	1223 m
Hank	60000 m	49358 m	24679 m	16453 m

Table 8 is based on the following formula [Gilb-Weedon, 1976], in which a plane earth is assumed. R represents the distance from the reference station to the range hole center in meters.

$$R = 2h_1 \frac{h_2}{kl}$$

The distance of the maximum expected signal is:

$$R_m = 4h_1 \frac{h_2}{(2k + 1)}$$

Where h_1 and h_2 are the heights in meters of the reference and the master stations respectively, l is the wavelength and k is an integer (k = 1,2,3,...).

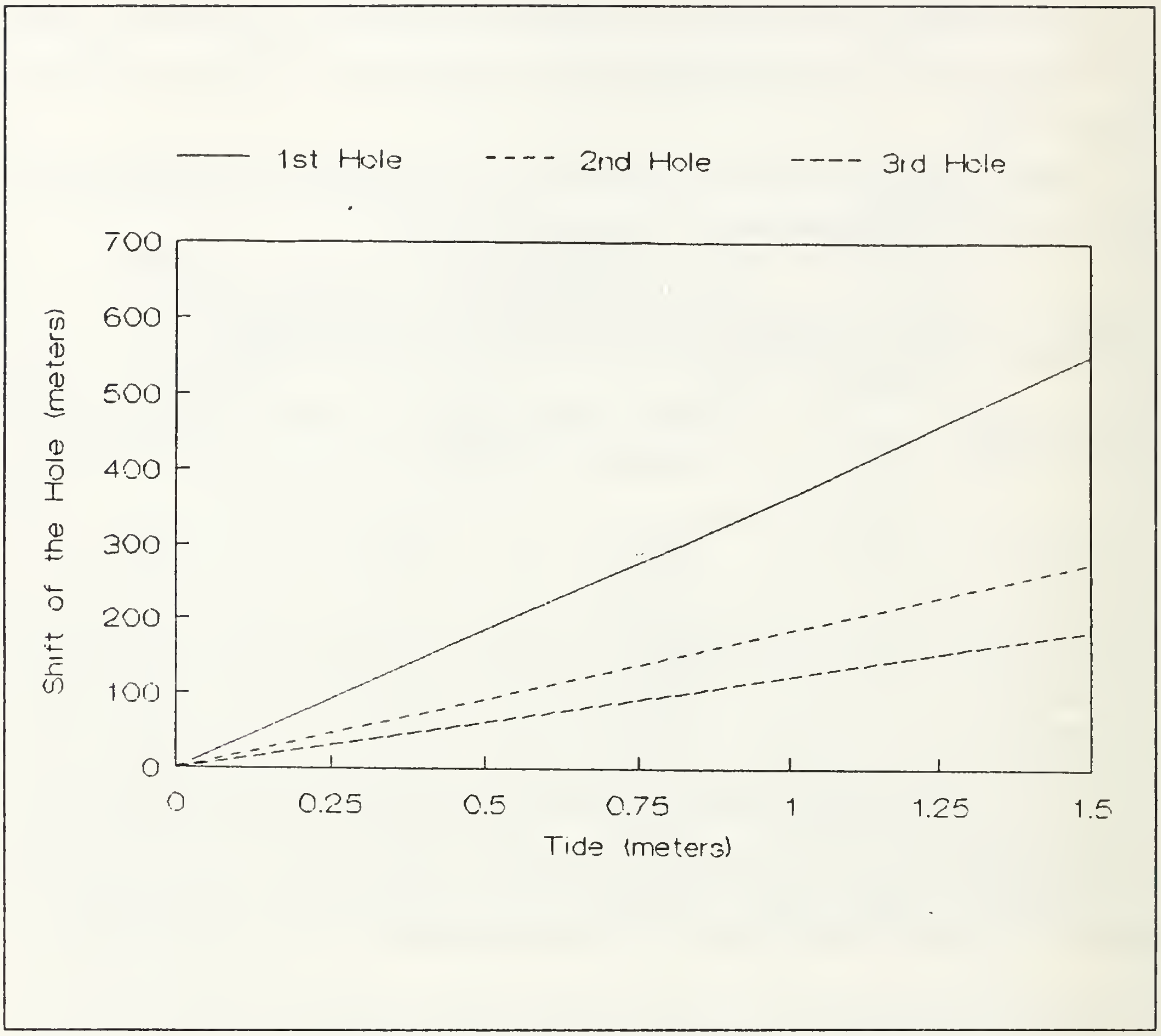

Figure 10. RANGE HOLE SHIFT VS TIDAL HEIGHT

In the Bay there is a sea level variation due to tidal effects of 6 to 7 feet maximum. This effect tends to shift the range hole center towards the shore station at high water and away from the shore station at low water. The overall effect of this phenomenon for the stations appear in Figure 10, for each range hole.

Typical wind and wave conditions in the Bay are such that 'perfect' signal reflections are not expected. Thus range hole problems should be rare and limited to conditions of calm sea accompanied by light winds. Range hole phenomena were not detected in the positioning data studied.

H. CRITICAL SIGNAL THRESHOLD (CST) DERIVATION

The relatively large distances and varying propagation conditions encountered in the Monterey Bay network result in many low signal strength readings. It is important that a method be found for using these readings if at all possible. Casey, 1982, has shown that low signal strength ranges can be used if corrected in postprocessing by an empirically derived relation between bias error, standard deviation, and signal strength.

The recommended procedure to establish this relation is to perform repeated range measurements over a known length baseline, with a variable attenuator to artificially vary the received signal strength. These attenuators were not avaliable, but the effect was achieved by ranging over relatively long baselines of several different lengths, in order to obtain readings over a spread of low and high signal strengths. Two sets of range readings were collected for different combinations of Master and reference stations, with signal strengths varying from about 5 to 25.

For each Master/Reference station pair, ranges with signal strength over 15 were averaged to estimate a mean range, free of low SS effects. Differences between this mean range and all low SS (< 15) ranges were computed, representing the additional error due to low SS. By this technique, error estimates from different Master/Reference station pairs could be combined without concern about systematic differences between equipment pairs. The resulting range error estimates were grouped by signal strength: 5-6, 7-8, 9-10 and so forth. Mean errors and standard deviations were then computed for each signal strength group as shown in Table 9. As expected, both the mean error and standard deviation tend to increase as the signal strength decreases.

The two data sets were compared to ensure repeatability of the results before deriving the empirical relation. In Table 9 we can see the results of the statistical tests for the two data sets. They are treated as samples from one population, but each with their own estimated means and standard deviations and examined with the Fisher - Behrens statistical test [Hamilton, 1964] at a 95% confidence level.

as follows. The T test limit was taken from the Student's t distribution table with degrees of freedom calculated by:

$$dof = \frac{\left(\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}\right)^2}{\frac{\sigma_1^4}{n_1^2(n_1 - 1)} + \frac{\sigma_2^4}{n_2^2(n_2 - 1)}}$$

The calculated value for the test is given by:

$$u = \frac{(\bar{x}_1 - \bar{x}_2) - (\mu_1 - \mu_2)}{\left(\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}\right)^{\frac{1}{2}}}$$

Where σ_1^2 and σ_2^2 are the estimated variances, μ_1 and μ_2 are the estimated mean errors, and n_1 and n_2 are the number samples in the first and the second data sets respectively.

We examine the hypothesis:

$H_o: \bar{x}_1 - \bar{x}_2 = 0$ The two data sets belong to the same population.

Against the alternative

$H_1: \bar{x}_1 - \bar{x}_2 \neq 0$ The two data sets don't belong to the same population. Table 9 shows the derived statistics from the two data sets and the limit of the T test in each case. Every calculated value, for the Fisher-Behrens statistical test, that is bigger than the T value means that the H_o hypothesis is rejected so something else going on in the data sets.

In the column 'Calculated value', the number is derived using the means and the standard deviation of the measurements. We can see that when SS is 5-6 and 17-18, the calculated value is bigger than the T test limit, which means that in these cases the null hypothesis is rejected.

The number given in the column 'Calculated value with increased σ ' is a combination of the standard deviation of the long term variation in the instrument and its observed standard deviation. As we can see the result is a total

Table 9. STATISTICAL TESTS FOR THE TWO SAMPLE DATA SETS

S.S	1st data set (mean error / σ)	2nd data set (mean error/ σ)	T test limit	Calcu-lated value (u)	Calcu-lated value with increased σ
5-6	15.1/4.5	13.5/5.3	1.98	2.48	1.78
7-8	8.1/3.7	7.8/3.8	1.98	0.63	0.41
9-10	4.5/3.0	3.8/2.6	1.98	1.68	0.98
11-12	1.9/1.7	1.9/1.7	1.98	0.28	0.19
13-14	0.3/1.8	0.3/0.7	1.98	0.28	0.2
15-16	-0.0/1.5	0.1/0.6	1.98	0.98	0.37
17-18	0.8/1.4	0.3/0.7	1.98	3.35	1.17

statistical agreement of the data sets. We conclude, therefore, that they belong to the same population.

The next step is the derivation of the equation that will permit the use of the lower SS more effectively. The equation derived was

$$y = \left(\frac{71.093}{\ln x} - 27.206\right)$$

Where y represents the mean error in meters and x the low signal strength and the given numbers represent meters. The resulted y value represents the observed minus the calculated (C-O) range correction.

Figure 13 shows this resulting best fitted curve. The correlation for the case is more than 0.999 which indicates that the resulting equation is very close to perfectly modelling the data. This equation can be included in the software as a correction for the lower SS rather than rejecting them below the CST.

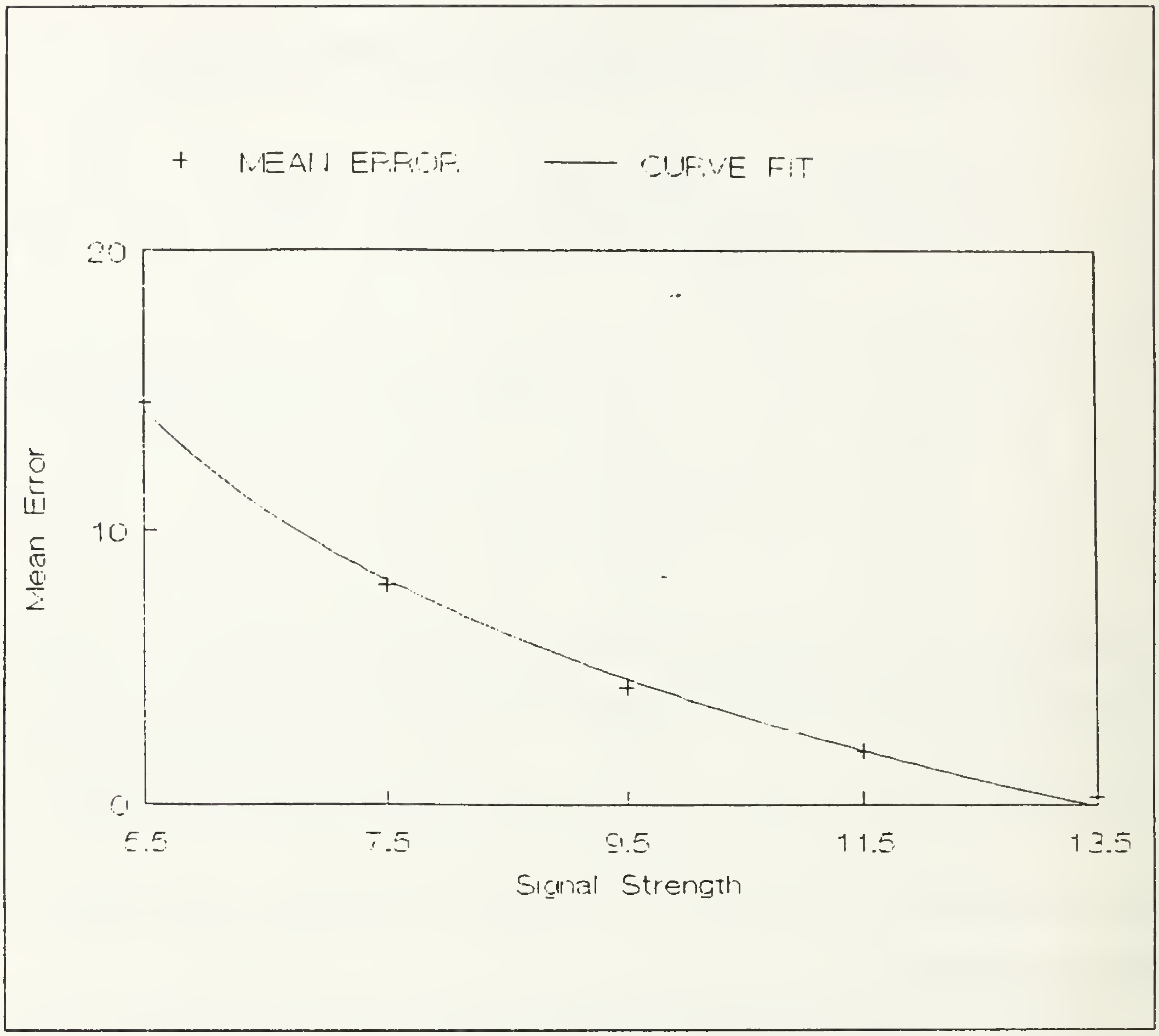

Figure 11. FITTED CURVE TO THE COMBINED DATA FOR TESTS 1 AND 2

Additionally, due to the increased standard deviation of the ranges at lower SS a higher value for standard deviation of a single measurement should be used in the weight matr.x formulation.

I. VARIATION OF THE STANDARD DEVIATION WITH TIME

Eigth sets of range measurements were collected over the known distance between station HAYS and geodetic station RANGE 7. The choosen distance was short (2341 m) to eliminate the effect on distance of the variation of weather

conditions. These 8 sets were collected on 8 different days and they have length of about 1 hour, with 3 second intervals between range measurements. Table 10 gives the bias of these measurements with respect to the known distance and the standard deviation of a single measurement. The results from Table 10 show that the system has a standard deviation which is indicative of its precision rather than its accuracy. In addition, it has a variable bias. The total standard deviation for the system must reflect both these components.

Table 10. STANDARD DEVIATION AND BIAS OF RANGE ERROR

NUM	Standard deviation	Bias
1	0.285	-0.725
2	0.206	1.447
3	0.255	1.324
4	0.266	1.531
5	0.374	0.577
6	0.856	0.007
7	0.576	0.501
8	0.541	1.173

The biases shown in Table 10 were used statistically to show that the standard deviation of one measurement is 2.54 meters, which concurs with the value derived by evaluation of σ_0^2 estimates in section C of this chapter. The procedure followed for this derivation was a simple multiplication of the standard deviation of the mean bias found from the data set by the square root of the number of data sets. The user shouldbe aware that the standard deviation can be larger on board a vessel in a rough sea due to mast movements and the selectivity of the

stations that the system makes(non simultaneous measurements to the reference stations). The bias variation from day to day makes the calibration of the stations time consuming because a one day calibration will not remove all the bias.

Table 11. MEAN DIFFERENCES AND STANDARD DEVIATIONS FOR STATIONS HAYS AND TREVOR

DISTANCE	Mean difference (Hays)	Standard deviation (Hays)	Mean difference (Trevor)	Standard deviation (Trevor)
SHORT	0.55	0.8	-	-
MEDIUM	1.02	0.55	0.91	0.48
LONG	1.27	0.75	1.48	0.68
V.LONG	1.28	1.2	0.84	0.95

J. VARIATION OF THE STANDARD DEVIATION WITH DISTANCE

The second thing was the variation of the standard deviation with the distance or with S.S. when it is above the CST. Several problems limited the data collection, like the unavailability of an attenuator, the poor network of known positions around the Bay and the low elevation of possible calibration sites. The data were sufficient only for the evaluation of station HAYS and partially of station TREVOR.

Table 11 shows the mean difference of the measured distances from the true distances and the standard deviations of each set of range measurements. We can see that there is variation of the mean error with distance in both stations but no indication exists that a function can be derived because the mean differences with the given standard deviations are not statistically different. Actually, a functional

variation of the standard deviation with distance was not expected, when operating above CST.

V. DISCUSSION AND CONCLUSIONS

The Mini-ranger network in the Monterey Bay was installed for research purposes by MBARI and NPS and was examined from various aspects. Useful results were drawn that can help in the understanding of the operation of transponder type systems in other areas, and that will make the present network more useful when operating at low SS.

Figure 12 shows the overall coverage of the Mini-ranger with all the limitations taken into acount, except that weather conditions can attenuate the signal and in turn reduce the maximum range of the stations. For the maximum range derivation a height of the master station on the ship was assumed to be 10 meters.

From this network and the data processed, the following conclusions can be drawn:

- For the calibration of such systems, if one wants the maximum accuracy that can be provided, a bias taken from single observations over known distances or with the baseline method may be not enough. It is better to use repeated observations and a mean corrector derivation.
- The positions of the stations in the Bay were, with the exception of station HANK, determined to a sufficint level of accuracy such that they were not responsible for some of the large range standard deviations.
- The software of the user is important in the position derivation and can cause unexpected errors if not properly validated.
- The meteorological conditions in the Bay can cause attenuation of the signal and, in turn, reduce the maximum range ability. The range error from the delay of the signal due to meteorological conditions does not exceed the 1.2 meters in the extreme conditions and is smaller than 0.2 meters under the usual operational conditions.
- Range holes in the Bay can occur, but should be rare due to usual windy Bay conditions and the modulated surface from the swell.
- We have shown that ranges measured at low SS need not be rejected, but can be corrected using an appropriate error function. This function may vary from system to system.
- We show that the standard deviation can be considered to consist of two components, the unpredicted bias, which is smaller when the system is well calibrated and the measured standard deviation of the data. Generally the

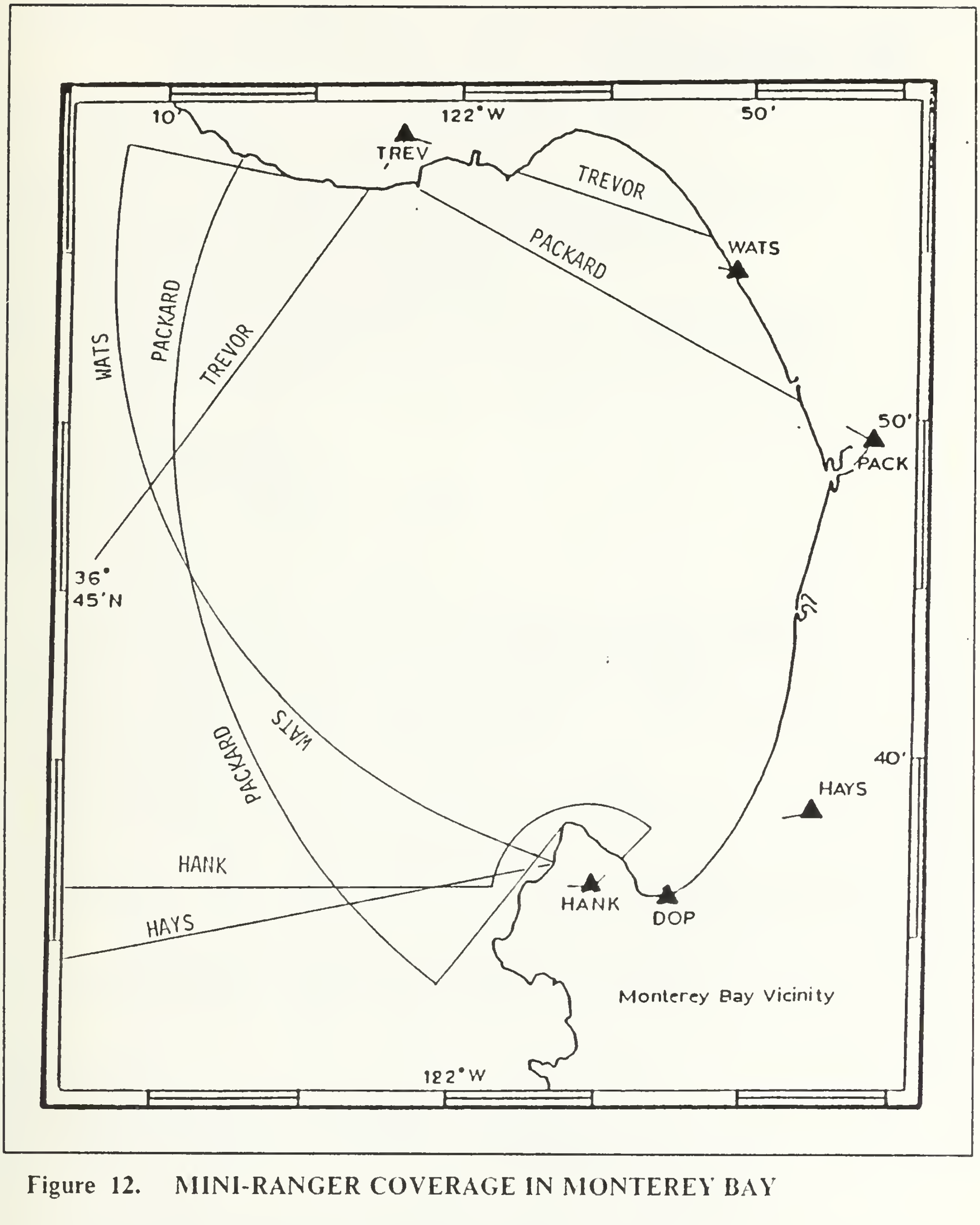

Figure 12. MINI-RANGER COVERAGE IN MONTEREY BAY

σ of one measurement under ideal conditions is a little greater than 2 meters. It is more proper to use σ = 3 meters when the system operates at sea.

- There are no indications for variation of the standard deviation with distance (or SS) above CTL.

APPENDIX A. COMPUTER PROGRAM LISTING

```
REM  PROGRAM "LESS"              FILE:  NICK3.BAS
'    NICK KRIONERITIS      Date: 8-8-89
'    Modified  10-17-89 by KJS
'*****************************************************************
REM This program calculates the optimum position of
'   a ship using  distances from known stations. It
'   serves the solution for a miniranger  network with
'   accuracy better than 10 centimeter.
' ****************************************************************
REM  The subrutine SOLVERANGX was changed from CDR K.SCHNEBELE
'    program "HYDROPLOT".
' ****************************************************************
$STACK 9216
$INCLUDE "SOLRANGX.SUB"
$INCLUDE "NICKMR.SUB"
ON ERROR GOTO ERRORHANDLER
Print "Enter the number of stations"
Input "N%=",N%
Lprint "Number of stations=",N%
'
'   DECLARATION OF THE VARIABLES
'   AP#(1): Approximate position of theship in meters (UTM)
'   SP#(2): Station positions in 2D array in meters (UTM)
'   R#(1): Ranges observed on the receiver in  meters
'   LX#(1): Stations  Eastings for the scale factor affection
'   X#(1): False Eastings of the stations
'   Y#(1): Northings  of the stations
'   Z#(1): Elevation s of the stations from MSL
'   SF#(1): Scale factor calculated for each case
'   W!(1): Diagonal Weight matrix assuming indepedence
'               among the measured ranges
'   CODE%(1): Index  numbers of the 4 stations in each record
'   AllSta#(2): UTM Coords (x,y,z) of 6 stations possible to  use
'
'       Vectors for SOLVERANG2 but not used in this version
'   CmOs!(1): Bias corrections for each of 6 stations
'   Wgts!(1): Weight  factor for each of 6 stations
'
'

DIM AP#(1:3)
DIM DYNAMIC SP#(1:N%,1:3) , R#(1:N%) , LX#(1:N%)
DIM DYNAMIC X#(1:N%)   , Y#(1:N%) , Z#(1:N%)
DIM DYNAMIC M#(1:N%)   , SF#(1:N%) , BRes#(1:N%) , W!(1:N%)
DIM code%(1:4),AllSta#(1:6,1:3),CmOs!(1:6),Wgts!(1:6)
'

PRINT "FREE ARRAY & STACK AT STARTUP", FRE(-1), FRE(-2)
CALL GetStations(AllSta#(),CmOs!(),Wgts!())
Lprint CmOs!(1);CmOs!(2);CmOs!(3);CmOs!(4);" CmOs"
CALL SetFiles
Print "Enter assumed  position"
Input "AX=",AP#(1)
```

```
Input "AY=",AP#(2)
Input "AZ=",AP#(3)
     LPRINT "Assumed Position";
     For i%=1 to 3
     Print "Assumed position in UTM (X,Y,Z)=" AP#(i%)
     LPRINT USING "#########.#"; AP#(i%);
     Next i%
' **********************************************************
REM Aproximations for calling the subrutine SOLVERANG2*
' **********************************************************
SFAC!=1.0        'Approximations for the subrutine for the
SHGT#=AP#(3)     '    corrections that have already done
AP#(3)=0.d0
LM#=1.1          'Convergence Limit test (meters)
Rm#=6368459     'Mean radius of Earth in meters     * 0.9996
' *******************************************
REM:Declaration of Weight matrix *
' *******************************************
              For i%=1 to N%
        W!(i%)=.25



             'Diagonal matrix assuming
        'independent measurements
        Next i%
'*******************************************
Beep 2: CLS
PRINT "Put Printer online in COMPRESSED PRINT Mode!"
PRINT "  Hit any key  when ready to continue"
WHILE NOT INSTAT
  LOCATE 2,37
  PRINT "_"
 WEND
 Print INKEY$
'
'  LOOP TO READ AND PROCESS ALL DATA UNTIL END OF FILE HIT
'
'WHILE NOT EOF(1)
For k%=1 to 500
   CALL READNICKMR(sec&,code%(),R#(),X#(),Y#(),Z#(),AllSta#())
' *******************************************
REM Correction for slope distance *
' *******************************************
     For i%=1 to N%
        If (R#(i%) > 1.d0), Then
        DHGT#=Z#(i%)-SHGT#
            HGT#=R#(i%)                2-DHGT# 2
            IF HGT#< 0.d0, Then
              PRINT "Warning - at time ";sec&;" DHGT exceeds Range"
              PRINT " Hit any key to continue"
              While Not INSTAT
              Delay 0.2
              Print ".";
              Wend
```

```
                Print INKEY$
          Else
                R#(i%)=SQR(HGT#)
                End If
          Else
                R#(i%) =0.d0
             End If
          Print "Ranges corrected for slope=" R#(i%)
          Next i%
' ****************************************
REM Calculation of the scale factors *
' ****************************************
AXP#=AP#(1)-500000
For i%=1 to N%
'
      LX#(i%)=X#(i%)-500000
      M#(i%)=AXP#              2 + AXP#*LX#(i%) + LX#(i%) 2
      SF#(i%)=0.9996 + .9996*M#(i%) /(6*Rm^2)
      Print "Scale Factors for UTM=" SF#(i%)
      '  Lprint "Scale factors for UTM="SF#(i%)
' ****************************************
REM Correction for the scale factors *
' ****************************************
      R#(i%)=R#(i%)*SF#(i%)
      Print "Corrected ranges=" R#(i%)
      ' Lprint "Corrected ranges=" R#(i%)
      Next i%
' ********************************************
REM Formation of station position matrix   *
' *********************************************
      For i%=1 to N%
      SP#(i%,1)=X#(i%)
      P#(i%,2)=Y#(i%)
      SP#(i%,3)=0.d0
      Next i%
'
CALL SolveRangX(AP#(),SP#(),R#(),CmOs!(),N%,SFAC! , W!(), LM# ,BRes#(),_
               sxx! , syy! , sxy! , variance! )
CALL RiteSol(sec&,AP#(),code%(),R#(),BRes#(),sxx! ,syy! ,sxy! ,variance! )
'
LPRINT USING " ###### #######.# #######.#"; sec& AP#(1) AP#(2);
For i% = 1 to 4
  LPRINT USING " #### ####.# +##.#"; code%(i%) R#(i%) BRes#(i%);
 Next i%
LPRINT USING " ###.####.# +###.# ####.#"; sxx! syy! sxy! variance!
'WEND
'
Next k%
CLOSE #1
CLOSE #2
END
ERRORHANDLER:
PRINT "FREE AT ERROR",FRE(-1), FRE(-2)
PRINT "AN ERROR TYPE", ERR, "HAS HAPPEN AT", ERADR
END
'*******************************************************
```

```
'*****************************************************************
$INCLUDE "openfile.sub"
'*************** GetStations Subroutine ************** kjs:Oct 89 *
'   file:NICKMR.SUB
SUB GetStations(AllSta#(2),CmOs!(1),Wgts!(1))
LOCAL i%, s$, code%
'
CLS: PRINT "Insert Disk with File ST.DAT in Drive B:"
Print " Hit any key to continue when ready";
  While Not INSTAT
    Locate 2,37
    Print "!"
   Wend
   Print INKEY$
   CALL OPENFILE("I",1,"B:ST.DAT",128)
   For i% = 1 to 6
  INPUT #1, code%,AllSta#(i%,1),AllSta#(i%,2),AllSta#(i%,3),CmOs!(i%),_
           Wgts!(i%),s$
 Next i%
CLOSE #1
END SUB

'************* SetFiles Subroutine  ********************* kjs: Oct 89 *******
'                                                     file: NICKMR.SUB
'
'opens input data file of Miniranger values(as #1), and opens output file
' for the computed results (as #2)
'
SUB SETFILES
LOCAL s$,txt$,FiName$
'
CLS: s$ = " (Drive: path name.ext) "
PRINT "Enter MiniRanger data file for input" + s$;
INPUT FiName$
CALL OPENFILE("I",1,FiName$,128)
'
PRINT "Enter solutions file for output" + s$;
INPUT txt$
CALL OPENFILE("O",2,txt$,128)
PRINT #2, "Solutions from file "; FiName$
END SUB
'************* ReadNickMR  Subroutine ********************* kjs: Oct 89 ******
'                                                     file: NICKMR.SUB
'specific to read mini-ranger files (from #1) from Krionertis thesis work
'with time in secs & 4 station numbers & 4 ranges.
'
SUB READNICKMR(sec&,code%(1),rang#(1),X#(1),Y#(1),Z#(1),AllSta#(2))
LOCAL s$,i%,nucode%()
DIM DYNAMIC nucode%(1:4)
  '
  LINE INPUT #1, s$
  sec&=VAL(MID$(s$,8,7))
  For i% = 1 to 4
   nucode%(i%)=VAL(MID$(s$,11+4*i%,4))
   rang#(i%)=VAL(MID$(s$,22+9*i%,9))
'
```

```
'check nucode%(), if not same as code%() then get new station coordinates
' for the X#(),Y#(),Z#() arrays
'
    If (code%(i%) <> nucode%(i%)), Then
      code%(i%) = nucode%(i%)
      X#(i%) = AllSta#(code%(i%),1)
      Y#(i%) = AllSta#(code%(i%),2)
      Z#(i%) = AllSta#(code%(i%),3)
    End If
  Next i%
END SUB
'************RiteSol Subrutine ***************************** kjs: Oct 89*****
'                                                           File: NICKMR.SUB
'
'  Writes Miniranger Solution and error statistics to File #2
'
SUB RiteSol(sec&,AP#(1),code%(1),R#(1),BRes#(1),sxx!,syy!,sxy!,vari!)
LOCAL i%
'
PRINT #2, USING "###### #######.# #######.#"; sec& AP#(1) AP#(2);
f$ = "## ######.# +##.#"
For i% = 1 to 4
  PRINT #2, USING f$; code%(i%) R#(i%) BRes#(i%);
 Next i%
PRINT #2, USING " ##.## ##.## +##.## ####.##"; sxx! syy! sxy! vari!
END SUB
'****************************************************************************
'****************************************************************************
      'File = SOLRANGX.SUB
      '* * * * * * SOLVE RANGE POSITION (ver X) * * * SUBROUTINE  * * *
      '
      'Returns grid x,y in first 2 elements of apsn#()
      '
      'INPUTS:
      'apsn#(3)   = approximate position as grid x,y,z
      'spsns#     = station positions in 2D array as grid x,y,z
      ' (nsta%,3)   (array has nsta% rows by 3 columns for x,y,z)
      'ORS#(nsta%)= observed ranges to each station in spsns# row order
      'rangcor!(nsta%) = C-O corrections for each range reading
      'nsta%      = number of stations/ranges
      'scalefac!  = grid scale factor (grid:true ratio)
      'wgts!(nsta%) = weights for each range) (1/sigma
      'dxlim#    = convergence limit to stop iterating position
      '             solution (given in grid units - e.g. meters)
      'OUTPUTS:
      'apsn#(3)   = x,y position returned in 1st two elements
      '             (elevation of antenna, z, unchanged)
      'BRes#(nsta%) = residuals on observed ranges (ob-computed)
      'sxx!      = variance in x (from Inv(ATWA))
      'syy!      = variance in y
      'sxy!      = covariance of x & y
      'variance! = est of sigma-o (ΣWgt Sum(Res)/(nsta-2)))
      '
      $INCLUDE "LUDCMP.BAS"
      $INCLUDE "LUBKSB.BAS"
   SUB SolveRangX(apsn#(1),spsns#(2),ORS#(1),rangcor!(1),nsta%,scalefac!,
```

```
                wgts!(1),dxlim#,BRes#(1),sxx!,syy!,sxy!,variance!)
LOCAL A#(),spsn#(),ORa#,Ax#,Ay#,Bi#,ATW#(),ATWB#(),ATWA#(),Indx%(),
      sum#,iteration%,i%,j%,k%,YCol#(),ATWAInv#(),xdx%(), Btemp#()
DIM spsn#(1:3), ATWB#(1:2), ATWA#(1:2,1:2), Indx%(1:2),xdx%(1:4),_
    Btemp#(1:4)
'
i%=1
For j% = 1 to nsta%
  If ORs#(j%) > 1.d0, then
    xdx%(i%) = j%            'xref to non-zero ranges (range > 1m)
    INCR i%
   End If
 Next j%
nranges% = i%-1
'
DIM A#(1:nranges%,1:2), ATW#(1:2,1:nranges%)
SolveAgain:
For i% = 1 to nranges%
  ORa#=ORS#(xdx%(i%)) + rangcor!(xdx%(i%))
  For j% = 1 to 3
    spsn#(j%) = spsns#(xdx%(i%),j%)
   Next j%
   CALL RangeLOP(apsn#(),spsn#(),scalefac!,ORa#,Ax#,Ay#,Bi#)
   A#(i%,1)=Ax#
   A#(i%,2)=Ay#
   BRes#(i%)=Bi#             'Residual (o-c) on each range
 Next i%
'
'  Compute ATW ¢2,nranges%|, & ATWB ¢2|
'
For j% = 1 to 2
 sum#=0.d0
  For i% = 1 to nranges%
    ATW#(j%,i%) = A#(i%,j%)*wgts!(xdx%(i%))
    sum# = ATW#(j%,i%)*BRes#(i%)+sum#
   Next i%
  ATWB#(j%)=sum#
 Next j%
'
'  Compute ATWA ¢2,2|
'
For j% = 1 to 2
  For i% = 1 to 2
   sum# = 0.d0
   For k% = 1 to nranges%
     sum# = ATW#(j%,k%)*A#(k%,i%)+sum#
    Next k%
   ATWA#(j%,i%)=sum#
 Next i%,j%
'
CALL LUDCMP(ATWA#(),2,Indx%(),i%)
CALL LUBKSB(ATWA#(),2,Indx%(),ATWB#())
sum#=0.d0
For i% =1 to 2
apsn#(i%)=apsn#(i%)+ATWB#(i%)   'shifts position by dx,dy which has
   sum# = ATWB#2(i%)sum#    'been returned as ATWB() from LUBKSB
```

```
 Next i%
sum# = SQR(sum#)
If sum# > dxlim#, Then
  INCR iteration%
  If iteration% > 7, Then
    Beep 3
    Print "Position did not converge -- NO SOLUTION! ";
    Print Using "Delta Position = +#.#####meters"; sum#
    sxx! = 0.0: syy! = 0.0: sxy! = 0.0: var! = LOG10(sum#)
    EXIT SUB
   End If
  GoTo SolveAgain
 End If
'
'  Compute variance-covariance values from inverse of ATWA
'       sxx! = sigma-x          2
'       syy! = sigma-y          2
'       sxy! = sigma-xy
'
ERASE ATW#, spsn#                    'make some room in memory
DIM YCol#(1:2), ATWAInv#(1:2,1:2)
For j% = 1 to 2
  For i% = 1 to 2              'identity vector, YCol, to find
    YCol#(i%) = 0.d0           'inverse using back-substitution
   Next i%
  YCol#(j%)=1.d0
  CALL LUBKSB(ATWA#(),2,Indx%(),YCol#())
  For i% =1 to 2
    ATWAInv#(i%,j%)=YCol#(i%)
   Next i%
 Next j%
sxx! = CSNG(ATWAInv#(1,1))
syy! = CSNG(ATWAInv#(2,2))
sxy! = CSNG(ATWAInv#(1,2))
'
'  Compute estimate of unit variance = SUM(Res 2*wgts)/nranges
'     Note that range residuals are in BRes#()
'
If nranges% = 2, Then
   variance! = 9999           'signifies no variance computable
 Else
   sum# =0.d0
   For i% = 1 to nranges%
     sum# = Bres#(i%)    2*wgts!(xdx%(i%)) + sum#
   Next i%
   variance! = CSNG(sum#/(nranges%-2))
 End If
'
If nranges% < nsta%, Then          'Set residuals into proper channel
  For i% = 1 to nsta%
    Btemp#(i%) = 0.d0
   Next i%
  For j% = 1 to nranges%
    Btemp#(xdx%(j%)) = Bres#(j%)
   Next j%
  For i% = 1 to nsta%
```

```
          If nranges% = 2, Then Bres#(i%) = 0.d0
          Bres#(i%) = Btemp#(i%)
        Next i%
      End If
      '
      END SUB
      '
      '* * * * * * RANGELOP * * SUBROUTINE  * * * * * * * * * *
      '
      'Computes A matrix components Ax & Ay and grid range
      'for input to multiple-LOP solution algorithm.
      '
      'Inputs:  apsn#() = approx position x,y,z coordinates (grid)
      '         spsn#() = station x,y,z coordinates
      '         scalefac!= grid scale factor (point or line)
      '         ORa# = observed slant range
      '
      'Output:  Ax# & Ay# such that (Ax)dx+(Ay)dy = OR-CR
      '         OmCR# = Observed minus Computed range at apsn#
      'Note:  Observed range (OR) has been corrected for elevation
      '       differences and grid scale before comparing with CR.
      '
      SUB RangeLOP(apsn#(1),spsn#(1),scalefac!,_
                   ORa#,Ax#,Ay#,OmCR#)
      LOCAL i%,CR#,dx#()
      DIM dx#(1:3)
      '
      For i% = 1 to 2
        dx#(i%) = apsn#(i%)-spsn#(i%)
      Next i%
      CR# = SQR(dx#(1)                2+dx#(2) 2)
      Ax# = dx#(1)/CR#
      Ay# = dx#(2)/CR#
         dx#(3)=0.d0
      OmCR# = ORa#*scalefac! - CR#
      END SUB
'******************************************************************************
'******************************************************************************
'                          file: OPENFILE.SUB
'
'Opens a disk file using TBasic commands.  Preforms error checking and
'allows recovery from common mistakes.
'
'INPUTS:  modes$ = One character designation for filemode
'                    "O" = for sequential output (to be written to)
'                    "I" = for sequential input (to be read from)
'                  ¢see Turbo Basic Ref, pg 282, for other choices|
'
'         FileNum% = file number to be used in read/write calls
'        FileName$ = Drive:/path/name.ext of file
'       RecLength% = record size in bytes, 1 to 32767, typical = 128
'
SUB OpenFile(mode$,FileNum%,FileName$,RecLength%)
'
 LOCAL errnum%, ans$
'
```

```
OpenSequence:
'
 ON ERROR GoTo ErrorHandling
 OPEN mode$,FileNum%,FileName$,RecLength%
 ON ERROR GoTo 0
 EXIT SUB
'
ErrorHandling:
'
  Beep 2
  errnum% = ERR
  Select Case errnum%
    Case 53,75,76
      Print "FILE or DRIVE PATH Not Found for ... ", FileName$
      Input "Re-Enter Drive: path name.ext -----> "; FileName$
    Case 68,71
      Print "DISK DRIVE NOT READY for ", FileName$
    Case Else
      Print "Opening File Gave Error Number ", errnum%
   End Select
  Input "(R)etry or (H)alt Program "; ans$
  If Ucase$(ans$) = "H", Then
      Resume HaltSequence
    Else
      Resume OpenSequence
   End If
'
HaltSequence:     'terminates main program
'
  Print "Program Halted!!!"
  Print "Subroutine OpenFile with Error Number ",errnum%
  Print "  encountered at program address ", ERADR
  END
END SUB
'**************************************************************************
'**************************************************************************
      'LU Back Substitution
      '
      ' Ref: Numerical Recipies, by WH Press, page 37
      '
      SUB LUBKSB(A#(2),N%,INDX%(1),B#(1))
      LOCAL 11%,i%,j%,sum#
      '
      ii%=0
      For i%=1 to N%
        11%=Indx%(i%)
        sum#=B#(11%)
        B#(11%)=B#(i%)
        If ii%<>0, then
          For j%=ii% to i%-1
            sum#=sum#-A#(i%,j%)*B#(j%)
           Next j%
        ElseIf sum#<>0.d0 Then
          ii%=i%
        End If
        B#(i%)=sum#
```

```
      Next i%
      '
      For i%=N% to 1 Step -1
        sum#=B#(i%)
        If i%<N%, Then
          For j%=i%+1 to N%
            sum#=sum#-A#(i%,j%)*B#(j%)
          Next j%
        End If
        B#(i%)=sum#/A#(i%,i%)
      Next i%
      END SUB
'************************************************************************
'************************************************************************
      'LU Decomposition Subroutine
      '
      ' Ref: Numerical Receipes, by WH Press, pages 34-36
      '
      SUB LUDCMP(A#(2),N%,Indx%(1),D%)
      LOCAL vv#(),Dum#,i%,j%,k%,imax%,aamax#,sum#
      STATIC nmax%, tiny#
      '
      nmax%=10
      tiny#=1.0D-20
      '
      DIM vv#(1:nmax%)
      '
      D%=1
      For i%=1 to N%
        aamax#=0
        For j%=1 to N%
          If ABS(A#(i%,j%))>aamax#, Then aamax#=ABS(A#(i%,j%))
         Next j%
         If aamax#=0, Then
            Print "Matrix has zero row # " i%
            Exit Sub
         End If
         vv#(i%)= 1/aamax#          'save row scaling factor
        Next i%
      '
      For j%=1 to N%
        If j%>1, Then
        For i%=1 to j%-1
          Sum#=A#(i%,j%)
          If i%>1 Then
           For k%=1 to i%-1
            Sum#=Sum#-A#(i%,k%)*A#(k%,j%)
           Next k%
          A#(i%,j%)=Sum#
          End If
         Next i%
        End If
      '                continuing j loop, searching for largest pivot
        aamax#=0
        For i%= j% to N%
          Sum#=A#(i%,j%)
```

```
      If j%>1, Then
        For k%=1 to j%-1
         Sum#=Sum#-A#(i%,k%)*A#(k%,j%)
        Next k%
       A#(i%,j%)=Sum#
      End If
      Dum#=vv#(i%)*ABS(Sum#)    'figure of merit for pivot
      If Dum#>aamax#, Then
        imax%=i%
        aamax#=Dum#
      End If
     Next i%
  '
    If j%<>imax%, Then
      For k%=1 to N%
        Dum#=A#(imax%,k%)       'interchange rows if reqd
        A#(imax%,k%)=A#(j%,k%)
        A#(j%,k%) = Dum#
      Next k%
     D%=-D%                     'change parity of D%
     vv#(imax%)=vv#(j%)
    End If
  '
    Indx%(j%)=imax%             'divide by pivot
    If (j%<>N%), Then
      If A#(j%,j%)= 0, Then A#(j%,j%)=tiny#
      Dum#=1/A#(j%,j%)
      For i%=j%+1 to N%
        A#(i%,j%)=A#(i%,j%)*Dum#
      Next i%
    End If
   Next j%
  '
   If A#(N%,N%)=0, Then A#(N%,N%)=tiny#
  END SUB
'**************************************************************************************************
'**************************************************************************************************
1,  585260.161, 4092490.284,  51.7, 0.0, 0.25, TREVOR
2,  602947.672, 4085231.399,  23.1, 0.0, 0.25, WATS
3,  609863.128, 4076611.345,  33.9, 0.0, 0.25, PACKARD
4,  607621.289, 4055915.264, 137.2, 0.0, 0.25, HAYES
5,  600434.009, 4051260.014,  10.0, 0.0, 0.25, DOPPLER
6,  596669.490, 4051826.411, 134.5, 0.0, 0.25, HANK
```

APPENDIX B. GEOMETRICAL ACCURACIES OF THE MONTEREY BAY MINI-RANGER NETWORK

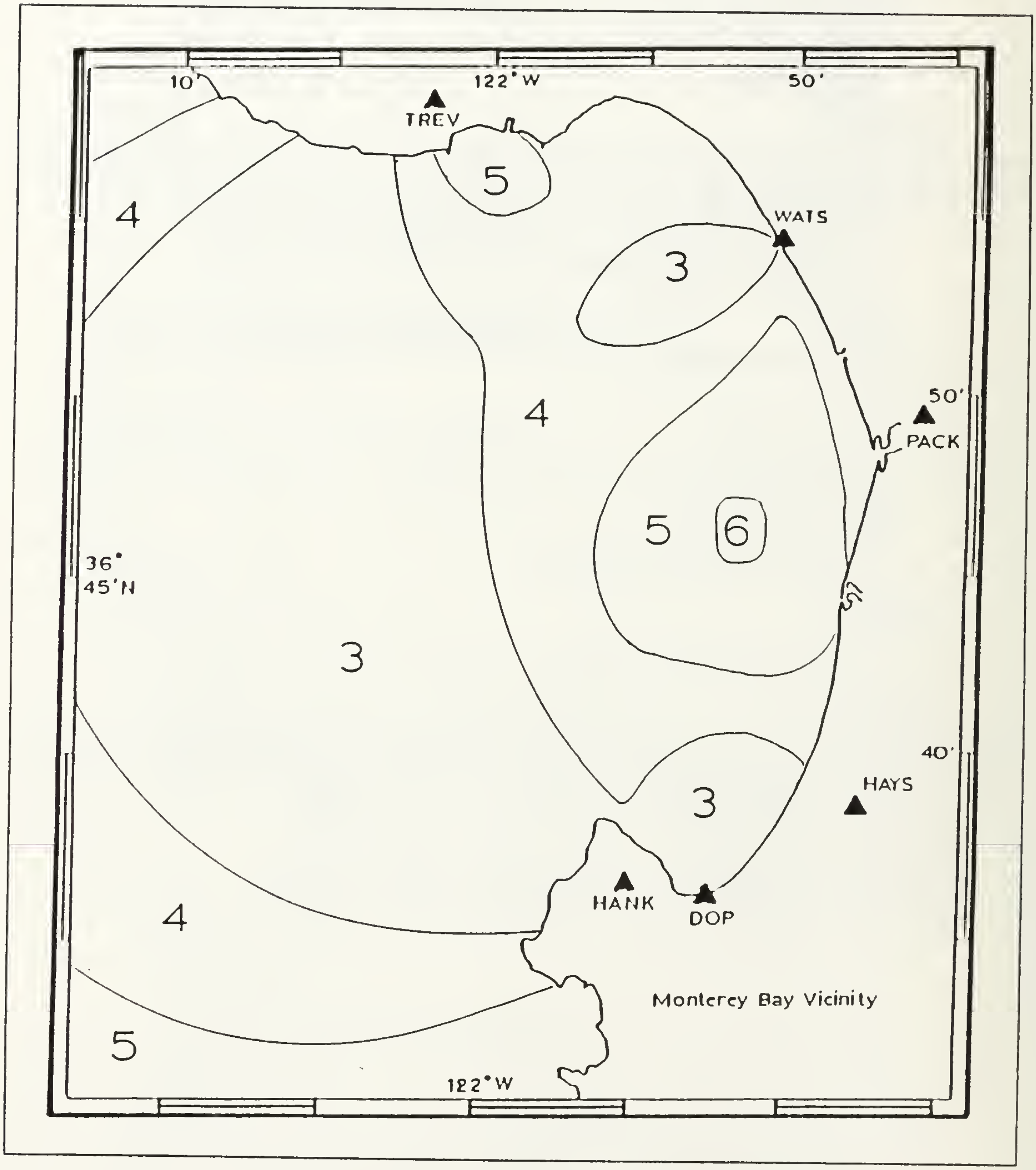

Figure 13. STATION COMBINATION TREVOR-WATS-HAYS-HANK

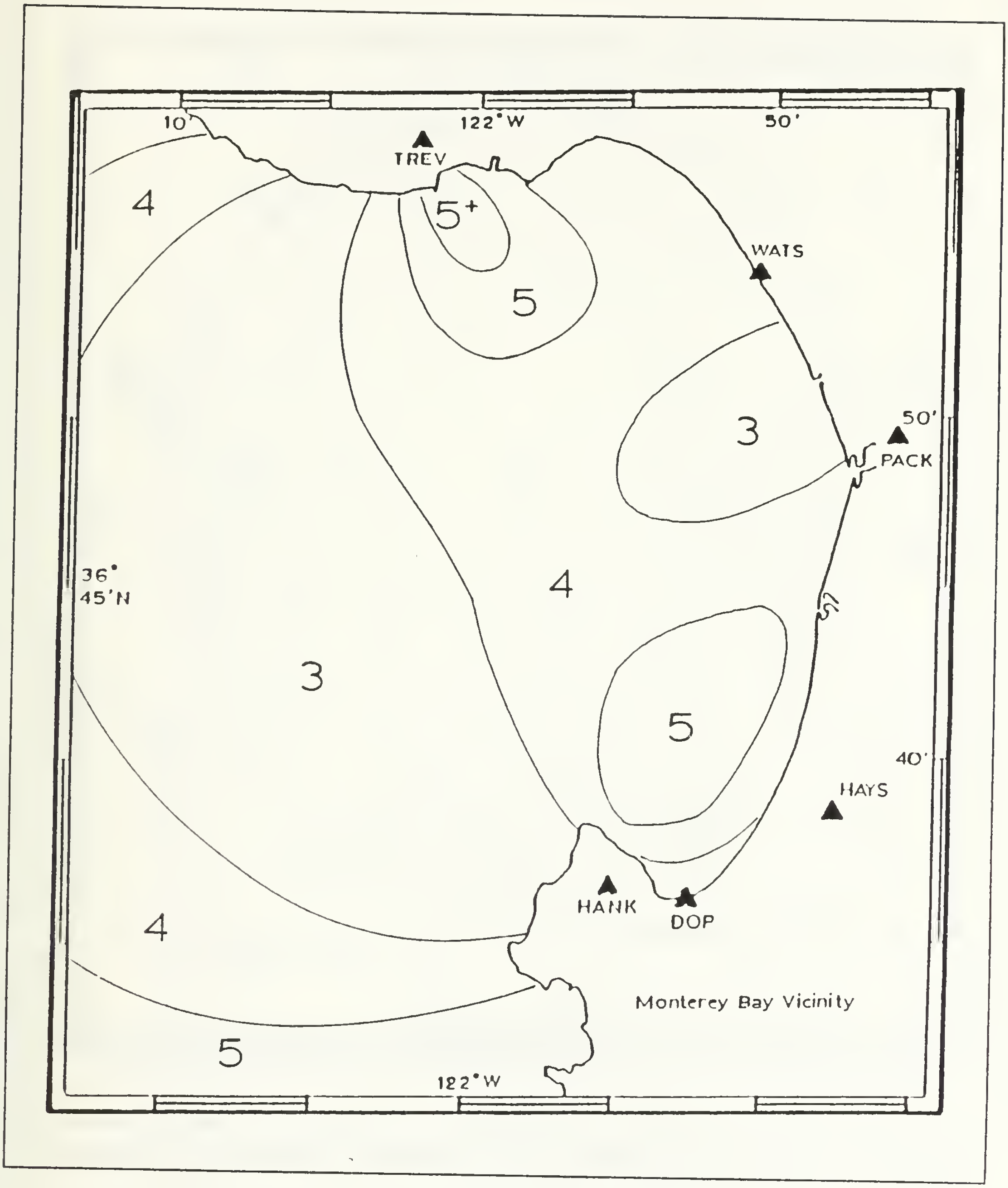

Figure 14. STATION COMBINATION TREVOR-PACKARD-DOPPLER-HANK

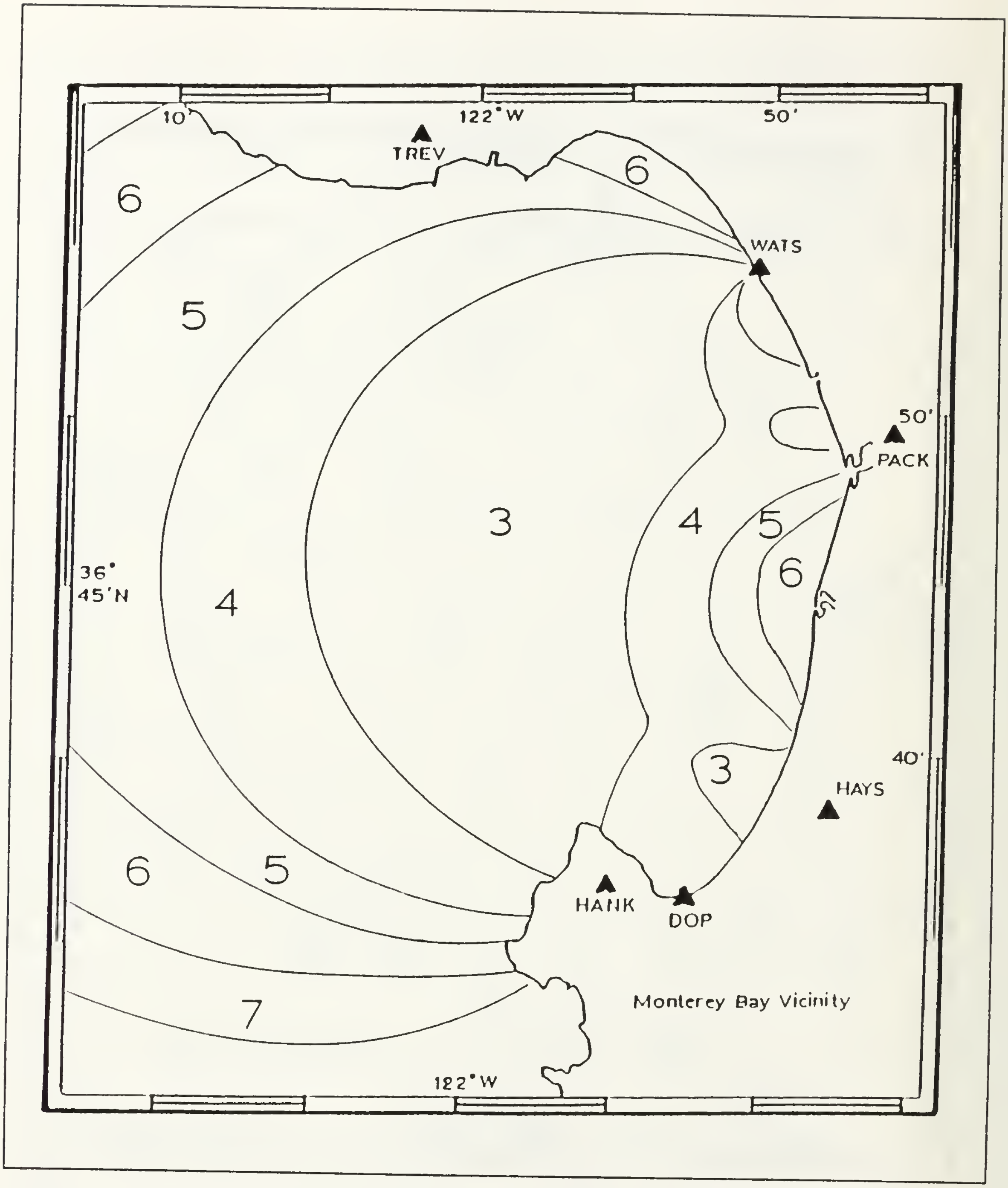

Figure 15. STATION COMBINATION WATS-PACKARD-HAYS-HANK

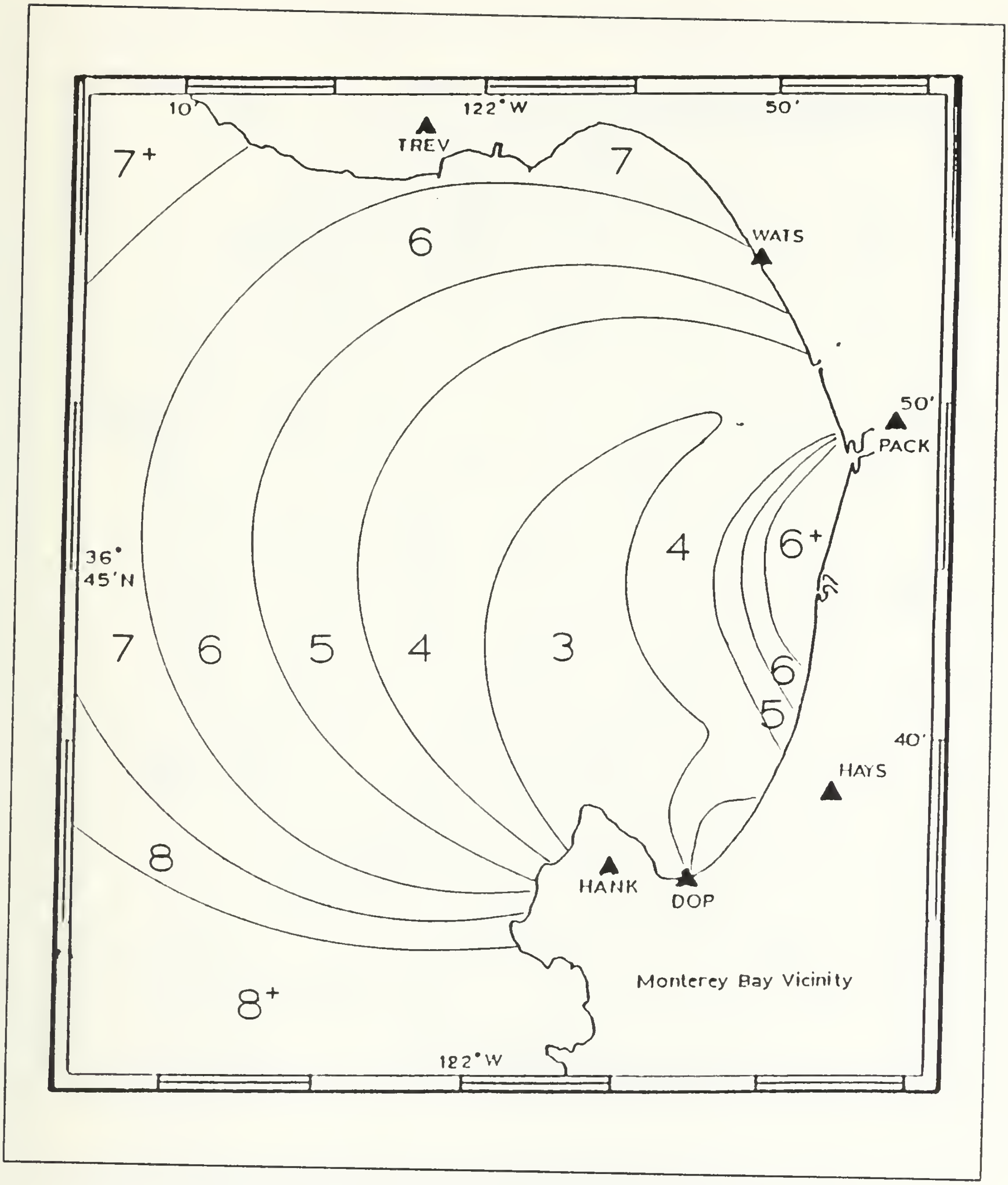

Figure 16. STATION COMBINATION PACKARD-HAYS-DOPPLER-HANK

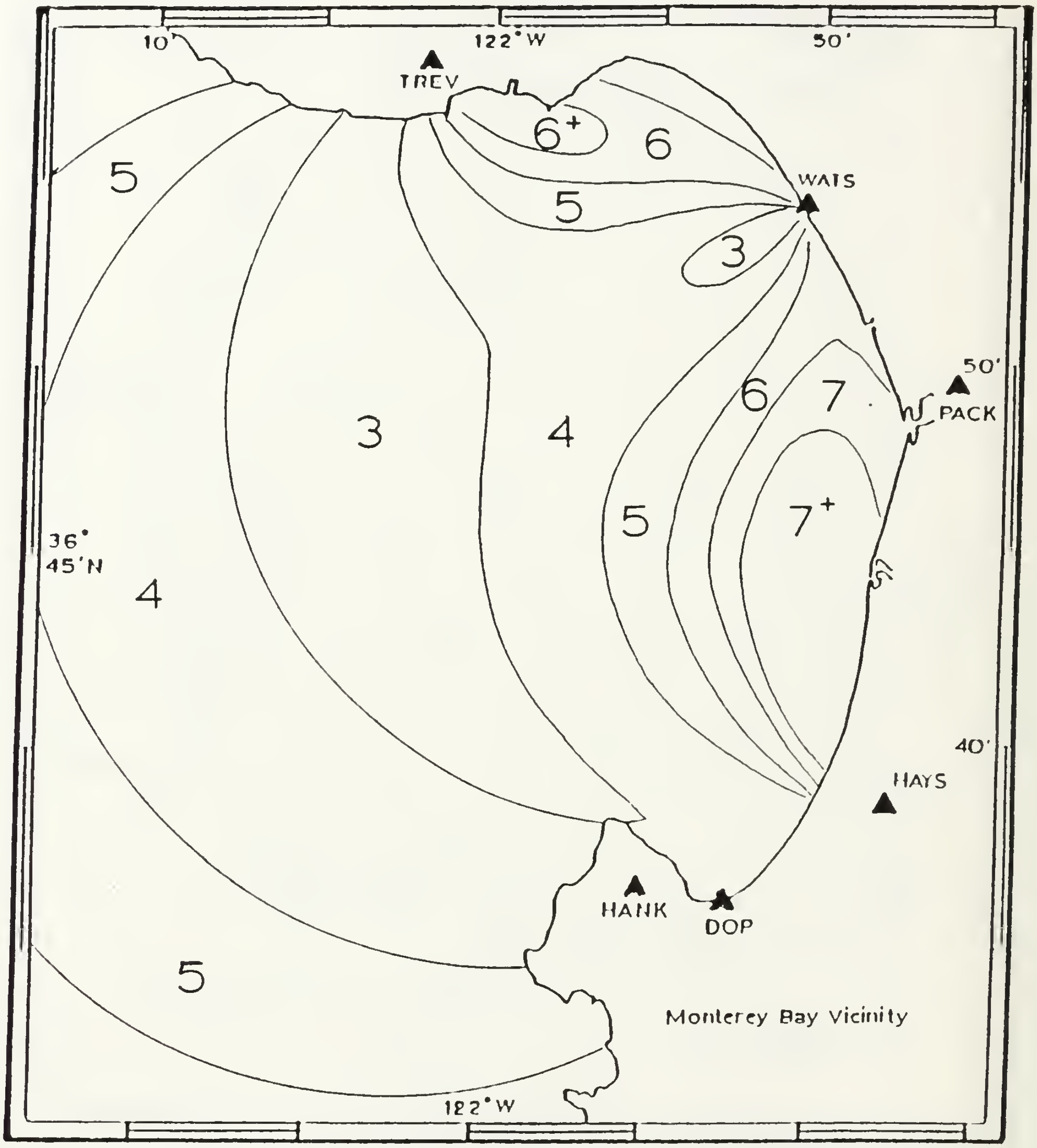

Figure 17. STATION COMBINATION TREVOR-WATS-HANK

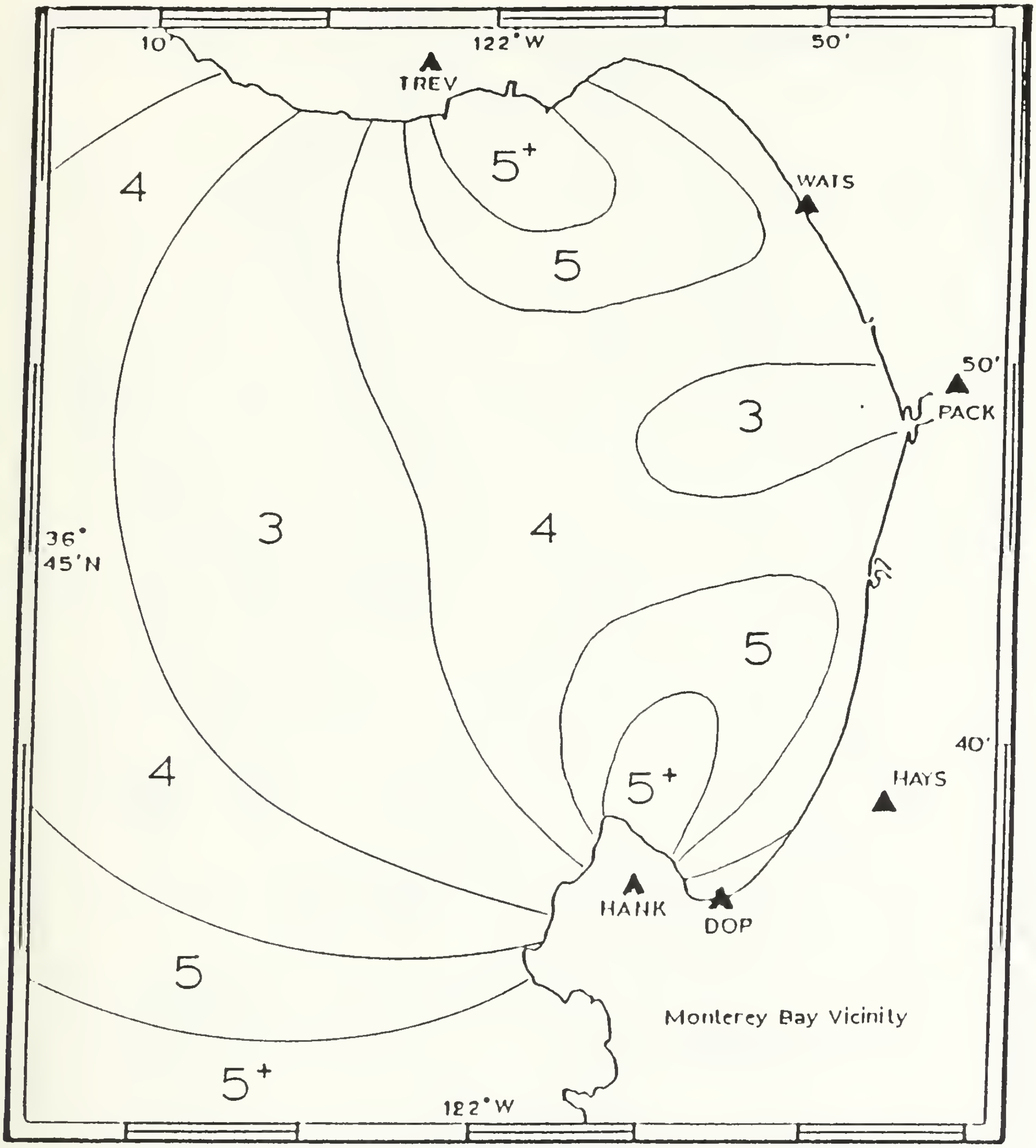

Figure 18. STATION COMBINATION TREVOR-PACKARD-HANK

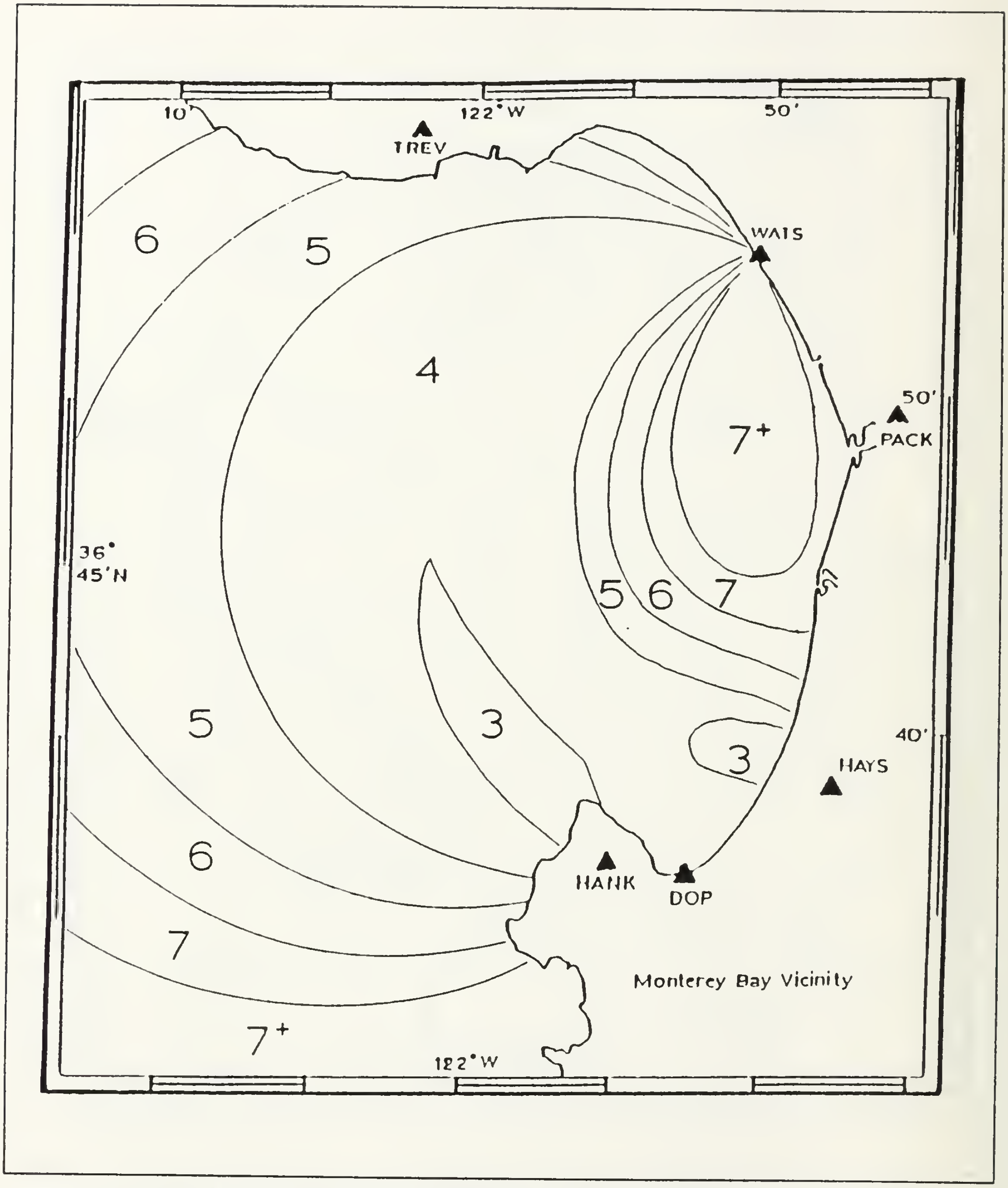

Figure 19. STATION COMBINATION WATS-HAYS-HANK

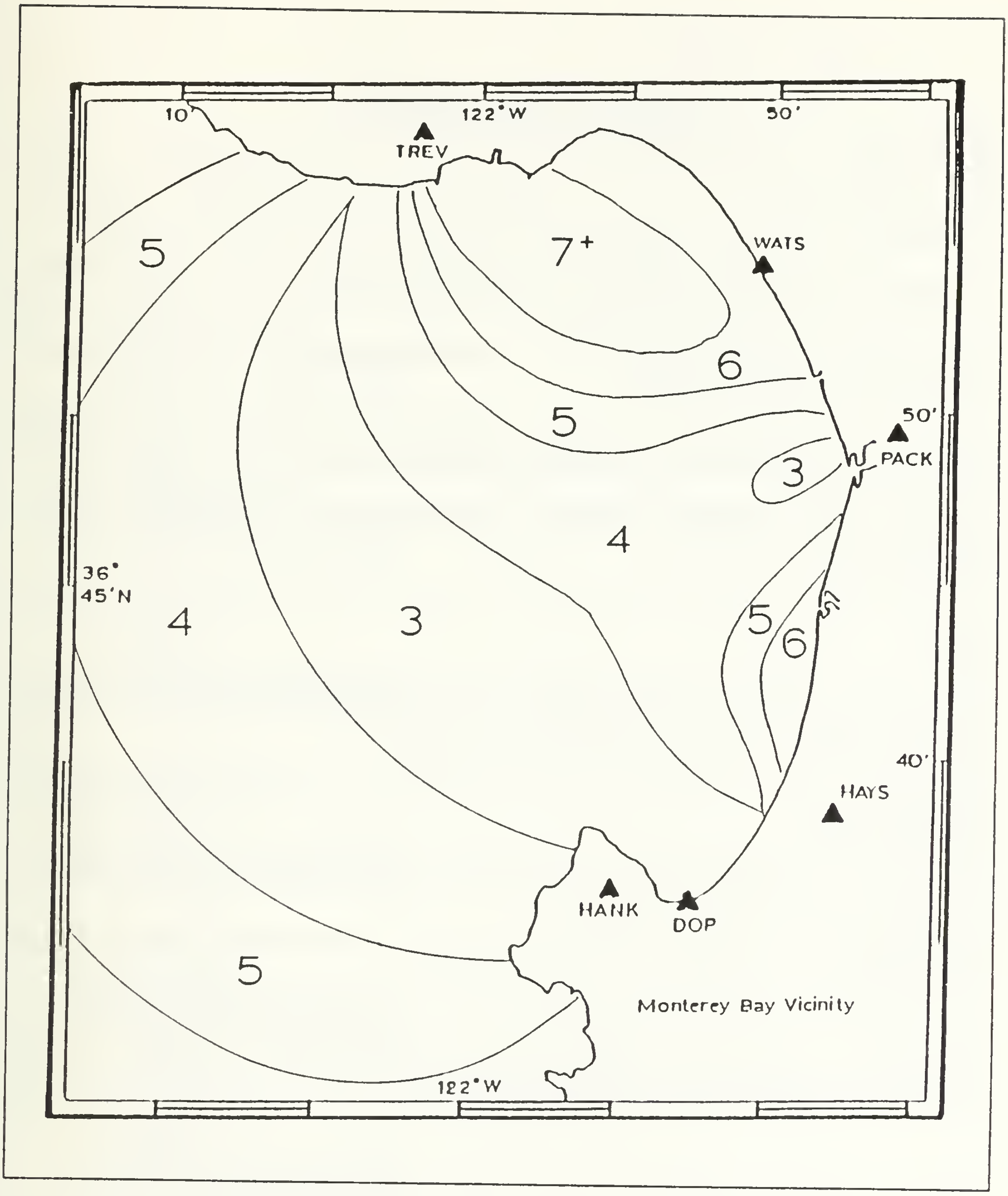

Figure 20. STATION COMBINATION TREVOR-PACKARD-HAYS

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